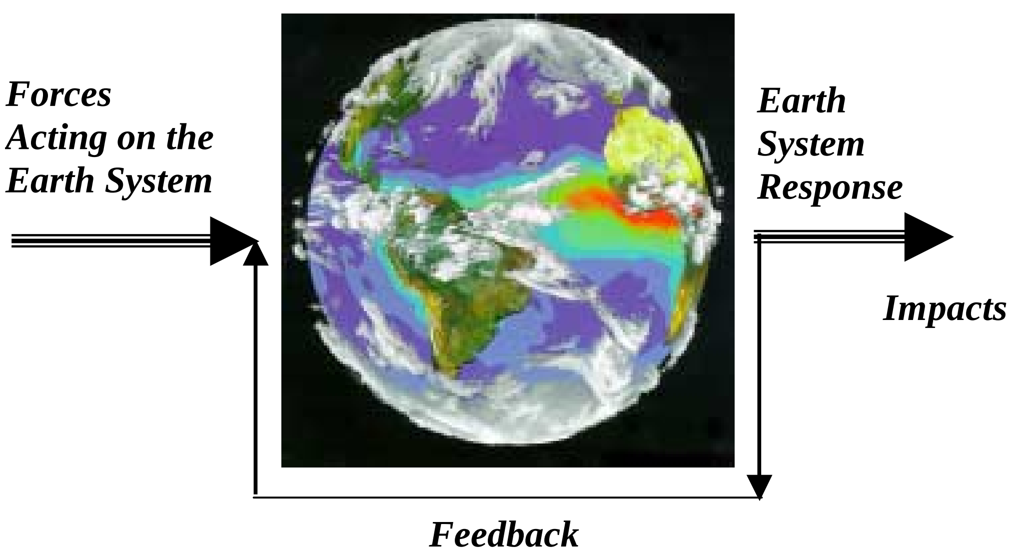
UNDERSTANDING EARTH SYSTEM CHANGE

NASA's Earth Science Enterprise

Research Strategy

for
2000-2010



December 2000

Preface

This Research Strategy has been prepared by NASA's Office of Earth Science in consultation with its Earth System Science and Applications Advisory Committee (ESSAAC) and selected members of the broader Earth science community. This edition incorporates comments from a formal review by the National Academy of Sciences.

The Research Strategy is one of a family of strategy documents being published to guide the Earth Science Enterprise for the new decade. Others are the Earth Science Enterprise Strategic Plan, Technology Strategy, and Applications Strategy. Underpinning this Research Strategy is a set of chapters (published separately) describing the planned activities under the principal research themes. The Research Strategy and these chapters constitute the Enterprise's Science Implementation Plan. The full set of Earth Science Enterprise planning documents can be obtained by visit the homepage at www.earth.nasa.gov.

NASA EARTH SCIENCE ENTERPRISE RESEARCH STRATEGY FOR 2000-2010

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Earth Science Enterprise Research Strategy for 2000-2010
Executive Summary

The mission of NASA's Earth Science Enterprise (ESE) is to develop a scientific understanding of the Earth system and its response to natural or human-induced changes to enable improved prediction capability for climate, weather, and natural hazards. The Earth Science Enterprise has three basic activities: a **research** program to increase in our knowledge of the Earth system, an **applications** program to demonstrate practical use of Earth system information to decision-makers in governments, businesses, and elsewhere, and a **technology** program to enable new or lower cost capabilities for the study of the Earth system in the future. NASA's unique capabilities in satellite and suborbital observing systems, information systems, and global models combine to provide the continuing advances in these three areas. This plan, the "NASA Earth Science Enterprise Research Strategy for 2000-2010" describes the strategy that ESE is taking through the new decade for the conduct of its research programs. Separate documents describe the plans for ESE's applications and technology programs, although each will reflect the crucial links between these areas.

The NASA Earth Science program is driven by the recognition of the societal importance of the natural variability of the planetary environment and the realization that humans are no longer passive participants in the evolution of the Earth system, but are instead causing significant changes in atmospheric composition, land use and land cover, water resources, and biodiversity. NASA embraces the concept of "Earth system science" – the idea that the Earth can only be understood as an interactive system that includes the atmosphere, oceans, continents and life. This concept of Earth system science goes far beyond the traditional Earth science disciplines to include a strong focus on interdisciplinary science to understand the interactions between the Earth system components. NASA also clearly recognizes the societal importance of Earth system science, as the scope and pace of natural and human induced changes occurring in the Earth system combine with increasing pressures on land, water, and air resources to increase the demands for accurate environmental information about the present and future.

Earth system science is a highly international and diverse discipline that cannot be studied by a single agency alone. NASA's Earth Science Enterprise is a part of a larger national effort, the multi-agency United States Global Change Research Program (USGCRP) as well as integrated with international scientific activities such as the World Climate Research Program and the International Geosphere-Biosphere Programme. NASA's contributions are the unique vantage point of space, the use of high performance aircraft, innovative remote sensing and in situ measurement techniques, and the development of large-scale data systems and computationally demanding global models designed to assimilate global environmental data and simulate Earth system behavior. NASA's strategy is designed to complement that of other national and international partners, but recognizes that the ESE goals, like those of its counterparts, are to provide answers to scientific questions and deliver objective scientific information to environmental decision-makers. As such, NASA has an "end-to-end" strategy to assure that all the information, understanding, and capabilities derived from its research programs achieve maximum usefulness to the scientific and decision-making communities. Also, it is important to note that the ESE has a single research program, in which space observations, ground-based and atmospheric in situ observations, laboratory process studies, and computational modeling and data analysis all work together to provide the needed answers and information.

The Earth Science Enterprise has defined its Research Strategy around a hierarchy of scientific questions. At the highest level, the Enterprise is attempting to provide an answer to the one overarching question **"How is the Earth changing and what are the consequences for life on Earth?"** The magnitude and scope of this question are too large to allow a simple answer. The next tier of questions provides a structure constituting the conceptual approach ESE is taking to improve our knowledge of the Earth system.

- ***How is the global Earth system changing?***
- ***What are the primary forcings of the Earth system?***
- ***How does the Earth system respond to natural and human-induced changes?***
- ***What are the consequences of change in the Earth system for human civilization?***
- ***How well can we predict future changes in the Earth system?***

These five questions define a pathway of "variability, forcing, response, consequence, and prediction" that is taken to further enumerate more specific questions (in Table 1) which provide direction and focus to the program. This structure highlights one of the most important and intellectual challenges of the study of the Earth system – that most responses the Earth system makes to a forcing (either natural or human-induced) can in turn become a forcing factors themselves. This is the definition of a feedback process. Thus, the understanding of feedback processes in the Earth system is central to NASA's study of the Earth system. The third tier of questions refines and delimits the components of and processes within the Earth system of particular interest to ESE.

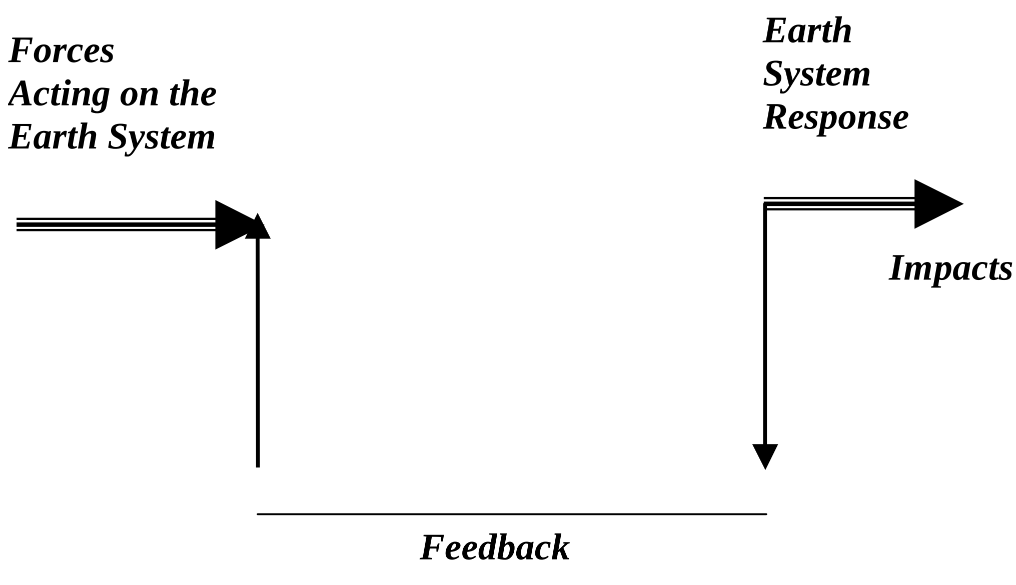


Figure 1: Earth System Conceptual Diagram

Hierarchy of Science Questions

Overall: ***How is the Earth changing and what are the consequences for life on Earth?***

- ***How is the global Earth system changing?(Variability)***
  - How are global precipitation, evaporation, and the cycling of water changing?
  - How is the global ocean circulation varying on interannual, decadal, and longer time scales?
  - How are global ecosystems changing?
  - How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?
  - What changes are occurring in the mass of the Earth's ice cover?
  - What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes**?**

- ***What are the primary forcings of the Earth system? (Forcing)***
  - What trends in atmospheric constituents and solar radiation are driving global climate?
  - What changes are occurring in global land cover and land use, and what are their causes?
  - How is the Earth's surface being transformed and how can such information be used to predict future changes?

- ***How does the Earth system respond to natural and human-induced changes?(Response)***
  - What are the effects of clouds and surface hydrologic processes on Earth's climate?
  - How do ecosystems respond to and affect global environmental change and the carbon cycle?
  - How can climate variations induce changes in the global ocean circulation?
  - How do stratospheric trace constituents respond to change in climate and atmospheric composition?
  - How is global sea level affected by climate change?
  - What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?

- ***What are the consequences of change in the Earth system for human civilization?(Consequences)***
  - How are variations in local weather, precipitation and water resources related to global climate variation?
  - What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
  - What are the consequences of climate and sea level changes and increased human activities on coastal regions?

- ***How well can we predict future changes in the Earth system? (Prediction)***
  - How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?
  - How well can transient climate variations be understood and predicted?
  - How well can long-term climatic trends be assessed or predicted?
  - How well can future atmospheric chemical impacts on ozone and climate be predicted?

- How well can cycling of carbon through the Earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane by these models?

The scientific breadth of Earth system research is enormous. A brief summary of the subjects considered in each of the five areas identified above follows:

• **Variability:** includes the internal variability of the coupled atmosphere-hydrosphere-biosphere system, with variability ranging from minutes to hours to days to all the way through seasonal, interannual, and longer timescales, as well as trends associated with human-induced changes, especially those occurring at decadal time scales (and longer). Emphasis is on global and large-scale regional variability.

• Forcing: includes naturally-occurring forcing factors such as solar irradiance, volcanic eruptions, and land surface evolution, as well as human-induced changes such as increased atmospheric composition of radiatively and chemically active gases and particulates, changes in land use and cover, and changes in availability and quality of water.

• **Response:** includes study of the processes that couple different components of the Earth system and give rise to feedback effects. Particular interest exists in the response of cloud distributions to changes in atmospheric circulation, the response of global ecosystems to changes in temperature, nutrients, and other factors, the atmospheric ozone response to precursors for both its production and destruction, and the response of polar ice to climate change.

• **Consequences:** includes study of local and regional impacts of changes that may be taking place on a global scale, as well as of the possible changes in the extremes of distributions of temperature and precipitation. Work on consequences is carried out through both the research and applications programs. ESE’s Applications program pursues demonstration projects applying Earth science, data and technology to areas of resource management, disaster management, community growth, and environmental quality. The ESE Application Strategy (ESE, 2000b) describes this program

• **Prediction:** includes the improvements of environmental predictions, especially those that can accrue from innovative use of new data types provided by ESE. These address issues such as climate and weather on time scales from day-to-day, seasonal, interannual, and decadal, as well as composition of the atmosphere, including pollutants such as ozone and radiatively active gases such as carbon dioxide and methane.

Given the wide range of disciplines and processes that could be productively studied, a number of prioritization criteria are defined to help in selecting and ordering both the specific scientific questions and programs to be implemented. From a scientific perspective, the following criteria are considered to be in descending order of priority, starting with Scientific Return; from the standpoint of implementation, they are listed in ascending order of priority:

• **Scientific Return:** the significance of the expected increase in our fundamental knowledge of some Earth system component or process, especially concerning the reduction of uncertainty, resolution of competing theories, or clear identification of the direction and magnitude of a feedback effect

• **Benefit to Society:** the extent to which the research outcome may be productively utilized on some relevant time scale for greater societal benefit (governmental, economic, individual)

• **Mandated Programs:** some NASA programs, such as the study of stratospheric ozone and continuity of the Landsat program, are required by law. Other activities may be given particular importance in the Federal budget at some point in time.

• Appropriate for NASA: the extent to which an activity makes valuable use of the unique capabilities of NASA, and could not be done easily by other governmental or private entities. In many (but not all) cases, questions addressed by NASA take place at large regional to global scales, involve seasonal and longer response periods, and deal with larger impacts than are questions addressed by other agencies.

• **Partnership Opportunity:** the extent to which needed work can be carried out in conjunction with partners, especially (but not exclusively) those of operational agencies in the US and abroad and partner space research agencies around the world.

• **Technology Readiness:** the extent to which current technology enables a question to be productively addressed (and activities implemented). Note that where interest exists and technology does not, investments by ESE's technology program can provide for the needed advances.

• **Program Balance:** to assure overall progress, it is important that resources be distributed in a way that ensures scientific progress is not impeded by the lack of key information about some particular Earth system component or process. This is especially true for improvements in understanding of consequences and capability for prediction, which could be severely limited by lack of understanding of variability, forcing factors, and response mechanisms.

• **Cost:** required resources must be available if a particular question is to be addressed or a mission is to be implemented.

The application of the prioritization criteria to the scientific questions presented allows for prioritization within each category (e.g., variability), but does not permit a linear priority ordering of all the questions. There is a logical progression associated with the research program, in that it is impossible to provide unambiguous answers to questions about consequence and prediction without a knowledge of the variability, forcing, and response processes that underlie them. However, it is not practical to defer all study of consequence and prediction until all uncertainties in the three other areas have been eliminated. The balance among the different areas may differ for different Earth system components or processes, and will evolve over time as the state of knowledge advances. NASA intends to periodically assess its progress on these priorities in consultation with the U.S. National Research Council.

The research program that will address the questions posed in this plan consists of several elements:

• **Basic Research and Data Analysis**: the conceptual source of Earth system science questions and strategies to address them. This part of the program provides the "feedback loop" and assures the results of scientific studies are helping to focus the scientific questions being addressed. It also includes the development of models that are used to integrate piecemeal findings, assimilate observed data and provide the predictive capability needed by ESE.

• Systematic Measurements: the long-term (typically but not necessarily continuous) measurement of a select number of critical environmental parameters, typically those that cannot currently be inferred from other parameters. For these measurements, the focus will be on the construction of consistent data sets from multi-instrument, multi-platform, and typically multi-year observations with careful attention to calibration and validation. These typically will involve incremental advances in technology rather than revolutionary innovations. By the end of this decade, an increasing fraction of these may be obtained from operational entities, as the quality, calibration, and availability of such systems are improved to meet scientific research needs.

• **Exploratory Measurements:** those observations that can yield new scientific breakthroughs by providing comprehensive information about a particular Earth system component or process. These are intended to be pursued for a finite period of time. They are likely to take advantage of innovative, even revolutionary, technologies.

• **Operational Precursor & Technology Demonstration Missions:** projects that aim to demonstrate new instrument and related technologies to either enable a transition to an operational environmental monitoring system, or to achieve a new capability for research. In the former case, such missions will be undertaken where the operational partner agency has a commitment and a plan to use them. Some operational precursor and technology demonstration missions are focused on reducing the cost of making measurements of established importance, while others focus on making measurements not possible or practical previously.

• **Data Management and Distribution:** the vast amounts of data that can be generated by ESE must be archived and distributed in a way to support their easy use by the science and applications communities. Data systems that can facilitate use of data and information, especially those of different types as needed for interdisciplinary science studies, are required.

• **Assessment:** it is important to "complete the cycle" of scientific research and assure that the large body of information obtained by the Enterprise goes through a synthesis process generates new or expanded knowledge of the Earth system. Organized national and international assessments are one essential means of ensuring that appropriate integration of separate findings is actually completed. Assessments support both the basic research and the applications communities, contributing to such major activities as the Intergovernmental Panel on Climate Change deliberations, World Meteorological Organization findings on ozone, and conclusions of the US National Assessment of climate change impacts. While assessments are important scientifically, they can also be starting components of a broader applications program.

Although the ESE research strategy is laid out in terms of variability, forcing, response, consequence, and prediction, much of its actual implementation will of necessity be carried out in a construct reflective of the components of the Earth system. The approach used most recently by NASA includes five "themes" – biology and biogeochemistry of ecosystems and the global carbon cycle; global water cycle; atmospheric chemistry, aerosols, and solar radiation; oceans and ice in the climate system; and solid Earth science. The first four of these thematic areas are closely aligned with those of the US Global Change Research Program, facilitating coordination of research with other US science agencies. An integrative modeling activity helps bring the individual components together to achieve our Earth system science goals. This approach is implemented with significant attention given to promoting close linkages between the traditional Earth science disciplines; the Earth system science concept has been the driving paradigm of ESE over the past decade, and this conceptual approach will only expand in the coming decade.

1. INTRODUCTION

The mission of NASA's Earth Science Enterprise (ESE) is to develop a scientific understanding of the Earth system and its response to natural or human-induced changes and improve prediction capabilities for climate, weather, global air quality and natural hazards. The Earth science research program aims to acquire a deeper understanding of the components of the Earth system and their interactions. These interactions occur on a continuum of spatial and temporal scales ranging from short-term weather to long-term climate scales, and from local and regional to global scales. The Enterprise also seeks to provide accurate assessments of changes in the composition of the atmosphere, the extent and health of the world's forest, grassland, and agricultural resources, and geologic phenomena that lead to natural hazards.

The NASA Earth Science program is driven by the recognition of the societal importance of the natural variability of the planetary environment and the realization that humans are no longer passive participants in the evolution of the Earth system. The world's scientific authorities share this view broadly. Responding to severe droughts and floods that revealed societal vulnerability to climate variations, the World Meteorological Organization, the International Council of Scientific Unions (ICSU), and UNESCO initiated in 1979 the World Climate Research Program, an international effort to understand the physical basis of climate. In 1982, NASA proposed a scientific program to acquire the knowledge "to ensure continuing habitability" of our planet in the face of expanding human populations and activities. The International Geosphere-Biosphere Program (IGBP) was established by ICSU "to describe and understand the interactive physical, chemical, and biological processes that regulate the Earth's unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions" (NRC, 1983). In 1988, the NASA Advisory Council charted a course for NASA's pursuit of Earth System Science (NASA, 1988).

The new scientific concept, Earth System Science, which emerged as the central paradigm of these national and international Earth Science programs is based on the recognition that: (1) the Earth can be understood only as an interactive system embracing the atmosphere, oceans and sea-ice, glaciers and ice-sheets, marine and terrestrial ecosystems, the land surface, and the Earth's interior; (2) new environmental problems are likely to arise, the solutions of which must draw on years of accumulated knowledge; and (3) science is a partner in national and international decision-making aiming to develop the potential to benefit society and to enhance economic security. There is no doubt that an integrated Earth system perspective would have eventually emerged as individual Earth science disciplines matured and global observing capabilities developed. However, a sense of urgency stemming from the observation of ozone depletion over Antarctica, evidence of widespread deforestation in the tropics, measurements of increased concentrations of carbon dioxide at Mauna Loa observatory, and model predictions of global climate warming led to the creation of the US Global Change Research Program (USGCRP) to "understand and respond to global change, including the cumulative effects of human activities and natural processes on the environment" (US Congress, 1990)..

NASA's contribution to the USGCRP is based on responding to this scientific vision with the unique capabilities which NASA brings to studies of the Earth system, and is designed to be part of the integrated national research program that constitutes the USGCRP. The use of the unique vantage point of space to study the entire Earth with technologically advanced remote sensing instruments forms the heart of NASA's contributions to this program. The global measurements which NASA provides will be used as input for scientific studies designed to address the critical global change and Earth system science questions addressed in this plan. High performance aircraft and innovative combinations of instruments and airborne and/or balloon platforms also provide important means for obtaining needed information; development of improved capability in these areas is facilitated by NASA's technology development activities. NASA's observational strategy is designed to complement those of the other USGCRP agencies, especially the in situ research and operational networks of its partners. In some cases (e.g., vertical profiling of oceanic properties) the in situ data are the only sources of needed environmental information. The calibration and validation of NASA data makes critical use of these observational programs of the other agencies.

The end-to-end approach described in this plan will include NASA's contributions to the USGCRP modeling and data assimilation efforts, as well as the role of more regionally-focused process-oriented campaigns that help provide the knowledge basis for interpreting remotely-sensed observations, understanding Earth system processes, and representing them in the global models used by all the USGCRP agencies. Through partnerships with other USGCRP agencies, as well as NASA's counterpart agencies around the world, efforts will be made to assure that the measurement capability developed by NASA can be sustained and utilized to facilitate the continued improvement and availability of global Earth system observations, understanding, and forecast capability in the future.
NASA's Earth Science Enterprise aims to obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales. The challenge is to develop the capability to predict those changes that will occur in the next decade to century, both naturally and in response to human activity. The strategic objective of the Enterprise is to provide scientific answers to the overarching question:

How is the Earth changing and what are the consequences for life on Earth?

In the words of the National Research Council/Committee on Global Change Research (NRC, 1999a), an important role of interdisciplinary Earth system science investigations is to prepare science for surprises. By definition, surprises cannot be fully anticipated, but they can be acknowledged as possibilities. A balanced research strategy in Earth system science should provide a broad enough observational basis to detect early manifestations of incipient unforeseen phenomena, and deep enough knowledge of the basic physical, chemical and biological processes involved to identify the likely causes. It is the special challenge for the NASA Earth Science strategy to cast the research net sufficiently wide (including laboratory and field studies as appropriate) to catch the unexpected, as well as respond to new contemporary science issues as they emerge.

The ESE has been seeking and will continue to seek the cooperation of national and international partners to maximize its investments' returns. In particular, the ESE actively cooperates with operational agencies to ensure the long-term continuity of key environmental measurements. To achieve this goal, NASA promotes the convergence of operational observation requirements with ESE's research data needs, and participates in the definition and development of precursor instruments and spacecraft technologies for future operational application missions. The ESE also aims to maximize synergism with related applied research programs conducted by partner agencies, especially the US Weather Research Program.

This document, which covers the period from 2000 to 2010, is one of several produced by the ESE to describe its activities. At the highest level is the Enterprise Strategic Plan (ESE, 2000a), while at the next level there is this document, describing the science research aims of the Enterprise and comparable documents representing its activities in the areas of applications, commercialization, and education (ESE, 2000b), and in technology (ESE, 1999). These three activities of the Enterprise work together to help assure that the advances in knowledge about the Earth system obtained through its research efforts achieve maximum societal benefit through their application by and communication to stakeholders in state and local governments, industry, and the general public. Synergy between research and technology activities ensures that the technology development program is driven by high priority science questions while its results are continually infused into the research program. Finally, close linkage between the research and education aims of the Enterprise ensures that tomorrow’s Earth science practitioners have the opportunity to engage in state-of-the-art research while learning about the Earth system through the integrated perspective of Earth system science. Readers are encouraged to examine these other ESE documents in order to further understand these other aspects of the program.

Concurrent with the development of these plans is a longer-term effort to provide a vision for ESE’s activities over the time period from 2010 to 2025. The longer-term, broader-scale effort is designed to more completely integrate the technology, research, and applications goals of the enterprise in a way that will allow for detailed end-to-end planning such that the scientifically and societally important questions posed can be answered, in particular with technological approaches specifically developed for that purpose. The resulting information will be provided to the scientific community and disseminated to the broader public through collaboration between NASA and its partners in the public and private sectors. For a fuller description of this longer-term planning process, the reader should examine the relevant document, which may be found at http://www.earth.nasa.gov/visions/index.html.

2. EARTH SYSTEM SCIENCE ISSUES

The key research topics studied by NASA’s Earth Science Enterprise fall largely into three categories: forcings, responses, and the processes that link the two and provide feedback mechanisms. This conceptual approach applies in essence to all research areas of NASA's Earth science program, although it is particularly relevant to the problem of climate change, a major Earth science-related issue facing the countries of the world. The scientific strategy to address this immensely complex problem can be laid out in five steps or fundamental questions, each raising a wide range of cross-disciplinary science problems.

- ***How is the global Earth system changing?***
- ***What are the primary forcings of the Earth system?***
- ***How does the Earth system respond to natural and human-induced changes?***
- ***What are the consequences of change in the Earth system for human civilization?***
- ***How well can we predict future changes in the Earth system?***

As will be seen below, each step in this logical progression of questions about Earth system changes necessarily touches upon practically all aspects of Earth system science. The questions also highlight the cross-disciplinary nature of global change research. This, by no means, downplays the significance of existing Earth science disciplines, nor the scientific importance of the complex interactive processes which govern the internal dynamics of individual Earth system components: the global atmospheric circulation and chemistry; the ocean circulation, the biogeochemical cycles; the mass balance of polar ice sheets and glaciers; terrestrial and marine ecosystems, and the solid Earth. Because of the importance and complexity of the processes involved in the internal dynamics of each component, and the scientific expertise accumulated in traditional Earth science disciplines that focus on these components, the most convenient organizational structure to plan the implementation of the ESE research program is an organization based on focused research themes, each addressing an individual component of the Earth system and key linkages with the other components. A final section on Earth system modeling completes the plan, and shows how knowledge from research on individual Earth system components can be integrated to provide quantitative answers to questions on forcings, responses, and future changes of the total Earth system.

In establishing such a discipline-based structure, it is crucial that sufficient attention be paid to scientific issues at the boundaries between two or more traditional scientific disciplines. Indeed, these are the issues that led to the development of Earth system science as a discipline in its own right. This conceptual picture of the Earth as an integrated system is deeply imbedded within the ESE planning process and will be reflected in the research which is solicited and selected by the enterprise.

2.1 Earth's Natural Variability

The Sun and Earth constitute an exceedingly complex dynamic system that generates variations on all time-scales, from minutes to days in the case of tornadoes and other severe weather disturbances, to many millions of years in the case of tectonic phenomena and erosion that shaped the Earth's landscapes, and the biogeochemical processes that conditioned the Earth's atmosphere and oceans. One may distinguish three types of natural variability of the Earth system: each must be characterized and understood in order to make science-based predictions about the Earth’s future evolution. The first type is the variability in the external forcing of the Earth by solar radiation and the extraterrestrial particles that reach the Earth and its atmosphere, such as those associated with solar proton events, as well as galactic cosmic rays and meteoric infall. Second is the variability generated within the Earth's interior, including the gravity and magnetic fields, the release of gases and particulate matter into the atmosphere from volcanic eruptions, geological processes such as earthquakes and erosion, as well as long-term effects associated with plate tectonics and motions deep inside the Earth. Third is the intrinsic variability of the Earth's atmosphere, hydrosphere, and biosphere, manifested in the interactive dynamics of the atmospheric and oceanic circulation, the global energy and water cycles, and the biogeochemical cycles. Even though variations in solar activity and volcanic eruption are, by right, natural phenomena, they constitute "external" forcing on the Earth climate system and the global environment, and will be considered in the next section (see Section 2.2)

The internal dynamics of the coupled atmosphere-hydrosphere-biosphere system are the principal source of natural variability. In the first place, the atmospheric circulation is by itself a chaotic dynamical system that constantly breeds new disturbances, from planetary perturbations such as the Quasi-Biennial Oscillations of the tropical stratosphere (which cycles over a period of about two years) to severe weather systems that generate heavy rain or snowfall as well as damage to human-built structures. Weather phenomena are not predictable on climate time scales (beyond one week or two), although their statistics are to some extent influenced by the more slowly varying aspects of the climate system, such as sea surface temperature. Since the latter do exhibit some predictability, the statistics may also have some degree of predictability. Weather phenomena do constitute a large background of random "meteorological noise", but nonetheless are important on account of their impact on society and their role in climate processes. Outside the tropics, the short-term variability of the atmospheric circulation is actually the main contributor to observed climate variations, and constitutes the background noise against which climatologists must strive to detect and quantify meaningful climate signals.

Most prominent among these longer-term signals are natural climate variations known as El Niño/ Southern Oscillation (ENSO) phenomena, that occur at random intervals of a few years and last one to two years. The evolution of ENSO phenomena is governed by a known predictable mechanism, involving the two-way coupling of the (upper) tropical oceans with the global circulation of the atmosphere. Once initiated, the evolution of individual ENSO phenomena can indeed be predicted with a reasonable degree of accuracy several months in advance. While the atmospheric manifestations of ENSO events are global, the region of most active interaction with the ocean is the tropical Pacific ocean, although significant ocean-atmosphere interactions occur elsewhere (e.g., Atlantic Ocean). Other similar but weaker modes of natural climate variability seem to exist on decadal time scales, but have not yet been fully characterized, much less explained and predicted (e. g. the Arctic Oscillation of the atmospheric circulation in the northern hemisphere, associated with the North Atlantic Oscillation). The complex linkages between atmospheric fluxes and ocean heat transport/storage lead to adjustments in the basin-wide circulation of the oceans on timescales from years to decades. Atmospheric variability and/or response to changes in ocean surface temperature affect surface winds, deep water formation, and ocean surface temperature and stratification. Considerable uncertainty remains, however, as to the mechanisms by which these longer-term variations modulate the shorter-term variations such as ENSO.

The significance of living systems as a factor in the Earth's natural variability, especially Earth's biogeochemical cycles, is a relatively recent discovery. The recognition of biotic factors as potential homeostatic controls of biogeochemical cycles has allowed for significant advances in our understanding of the natural metabolism responsible for the compositions of the atmosphere, oceans and sediments of planet Earth. It is estimated, for example, that the equilibrium global concentration of carbon dioxide in the atmosphere would be larger by about a factor 3 in the absence of the "biological pump" constituted by oceanic primary productivity. On the other hand, the CO_2 concentration would be smaller by about a factor 3 if the biological pump was operating everywhere at peak efficiency, compatible with available carbon.

2.2 Primary Forcings of the Global Earth System

The Sun is a mildly variable star that exhibits cyclical variations in its internal circulation and magnetic field, associated with minor changes in total radiation output but quite large changes in the ultraviolet part of the spectrum. Accurate measurements of solar radiation can only be made from space, due to the variable (and incompletely known) transmission of the Earth's atmosphere. Observed variations in total solar irradiance are believed to be too small to directly induce noticeable changes in the Earth's climate in the lower atmosphere. The larger variability in solar radiation at short wavelengths (UV and below) is known to affect the chemistry and composition of the stratosphere, with the magnitude of the effect increasing with altitude through the mesosphere and thermosphere. The possibility that these changes can induce sufficiently large changes in the troposphere to affect Earth's climate is a subject of active research. It is believed that, like similar stars, the Sun goes through occasional quiescent periods of low magnetic activity accompanied by a more substantial reduction in total radiation output. The most recent quiescent period occurred three centuries ago and may have been the cause of a general cooling observed in the Northern hemisphere during the "Little Ice Age". In addition, celestial mechanics impose quasi-cyclical variations in the parameters of the Earth orbit and rotation, thereby inducing major changes in the distribution of solar radiation incident upon the Earth surface and the timing of seasons, with still poorly understood consequences for the succession of glacial and interglacial climates (Milankovitch cycle).

Of a similar nature are changes generated by the motions of the Earth's interior, causing the accumulation of stress in the Earth's crust and occasional cataclysmic disturbances, such as earthquakes and volcanic eruptions. Gaseous emissions from the Earth's interior are, for the main part, a relatively quiet on-going process, notably on mid-ocean ridges where igneous matter from the mantle comes near the surface. Over geologic time ongoing gaseous emissions have helped determine the composition of the atmosphere. Major volcanic eruptions, on the other hand, can inject almost instantaneously very large amounts of trace gases and particulate matter directly into the Earth's troposphere, as well as trace gases into the stratosphere. Large volcanic eruptions, like that of Mt. Pinatubo in 1991, have noticeable global effects on climate and atmospheric chemistry, principally the creation of an enhanced layer of sulfate aerosols in the stratosphere which contribute to a drop in ozone levels that can persist for several years. Such volcanic eruptions constitute natural climate modification experiments: the study of the transient response to the temporarily increased burden of particulate matter is a means to gauge the sensitivity of planetary climate to forced changes in Earth radiation balance.

As human populations have grown and become more technologically advanced, they have increasingly left their mark on the Earth's environment. Human-induced changes in land cover and land use, resulting from agricultural practices, forest exploitation and clearing, grazing by domestic animals, wetland loss, urbanization, combustion, and development of industrial and transportation infrastructures, continue at a rapid pace and their effects (whether inadvertent, considered as a consequence of economic development, or deliberately made to enhance the functions of natural ecosystems) can now be seen from space over the whole Earth. In addition to the obvious disturbance of natural ecosystems, such changes may cause noticeable and widespread impacts on regional climate and hydrologic regimes, local and regional agricultural and fisheries productivity, soil erosion, sediment transport, and significant changes in land surface albedo and aerodynamic roughness, as well as changes in the biogeochemical cycling of carbon, nitrogen and other important elements. The implications of these changes for sustainable food production and resource management as well as the maintenance of a healthy, productive environment are a very serious concern for societies.

In recent times, however, the most significant anthropogenic forcing of the planetary environment has been the modification of the composition of the atmosphere, leading to rising concentrations of a number of reactive and radiation absorbing gases that contribute to depleting the stratospheric ozone layer and to increasing the atmospheric greenhouse effect. Measurements at the Mauna Loa observatory and several other stations have documented a recent upward trend of about 0.4% per year in atmospheric carbon dioxide (CO_2), amounting to a 30% increase in global atmospheric concentration since the beginning of the industrial era. The buildup of atmospheric CO_2, driven by the combustion of fossil fuels along with deforestation and other changes in land use, is the largest contributor to the global increase in the greenhouse effect. Quantifying the fraction of CO_2 from anthropogenic sources that accumulates and remains in the atmosphere (about half of total emission) is, in itself, a very complex problem, considering that CO_2 fluxes from the combustion of fossil fuels and changes in land use are but a small fraction of the large natural fluxes between atmospheric, terrestrial ecosystem, and oceanic reservoirs. However, since the natural processes have been “in balance” even seemingly small perturbations in the sources and sinks due to human activity can lead to significant changes in atmospheric CO_2 levels.

Many human enterprises, from natural gas extraction to animal husbandry and the intensive cultivation of rice, generate yet poorly quantified amounts of methane. Methane gas in the atmosphere is more effective on a per molecule basis at absorbing infrared terrestrial radiation than CO_2. Thus, the oxidation of methane at the source or subsequently in the atmosphere effectively reduces the overall impact on the greenhouse effect. Many other trace gases produced by human industry, such as the by-products of fertilizer usage, chemical pollution from internal combustion engines, or the purposeful synthesis of special chemicals by industry (e. g. chlorofluorocarbon compounds) also add to the overall greenhouse gas burden. Ozone, sensitive to a variety industry-produced compounds, also plays multiple climate forcing roles, through the absorption of solar ultra-violet radiation and terrestrial infrared radiation. The increase in tropospheric ozone over much of the world as a result of industrial activity has led to the contribution of ozone to radiative forcing being sufficiently important that it must be included in studies of climate forcing.

Another important forcing of climate is caused by natural and anthropogenic aerosols in the troposphere. The tropospheric aerosols produce a direct radiative forcing by virtue of scattering and absorbing solar radiation and an indirect forcing by changing the radiative properties of clouds. Radiative balance calculations suggest that the aerosol climate forcing can be comparable in magnitude but opposite in sign to that of anthropogenic greenhouse gases. However, the exact magnitude of the total aerosol forcing remains one of the largest unknown factors in climate research. It has even been speculated that the negative forcing of climate may have offset to a large degree the positive forcing due to the greenhouse gases, thereby temporarily masking much of the anthropogenic greenhouse effect.

Fires can effect large-scale, sometimes catastrophic, changes in land cover and terrestrial ecosystems, while creating large amounts of volatile pyrogenic materials, such as carbonaceous compounds and soot, that can disperse over very large atmospheric volumes and cause significant changes in the composition of the atmosphere and its radiative balance. The generation of fires and their ability to spread depends on climatological, ecological, and human factors (especially land use management). Fires also release trace gases and particulate matter into the atmosphere that can modify atmospheric chemistry and contribute to the greenhouse effect. Biogeochemical cycling in terrestrial ecosystems is profoundly affected by fires; nutrients can be made more available by fire and its after-effects on soils, they can be lost to the atmosphere in the form or trace gases or particulate matter, or they can be transported and deposited to distant ecosystems (both terrestrial and marine).

In addition, human activities induce environmental impacts on small, local spatial scales, including the withdrawal of water from ground water reservoirs, rivers or lakes, the release or disposal of toxic substances in the environment, the introduction of exotic species into local ecosystems, the fragmentation of habitats, the increase of sediment, nutrients, and pollutants in rivers and other aquatic ecosystems, and excessive demands on local biological resources (e. g. overfishing and overgrazing). Efforts designed to protect human communities (e.g., flood prevention, protection of local water supplies from salt inclusion) also will impact water availability and quality. The withdrawal of water results in enhanced evaporation, reduced river flow, and depletion of water reserves. The release of toxic chemicals results in disruptions of natural biogeochemical balances, stresses on the native flora and fauna, and even threats to human health. It is worth emphasizing that natural processes frequently connect large-scale and local forcings, and that the environmental impact of combined stresses may drastically exceed that from either one alone. Thus, it is important to understand the processes that connect human-induced disturbances and stresses on all scales.

2.3 Responses of the Earth System to Natural and Human-induced Disturbances

From a planet-wide perspective, observation shows that the primary indicators of the state of the Earth system vary from year to year and continue to evolve over periods of decades and longer. Long-term trends, in addition to inter-annual variations, are observed in the global atmospheric composition and circulation, Earth surface temperature, the global water cycle and total rainfall, the duration, frequency and severity of weather and hydrological phenomena, the ocean circulation and distribution of ice on Earth, global carbon cycle and total carbon storage in the Earth's oceans and terrestrial biosphere, the distribution and extent of global land cover, and the thickness of the global ozone layer. Establishing the existence of such trends against the background of geographic differences and transient fluctuations is a technical challenge, requiring full use of the resources (precision and global coverage) of modern observing techniques. In this regard, satellite observations have given us a powerful means to collect the required information systematically, globally, and under fully traceable conditions (notably, consistent sensor calibration).

The problem remains, however, of attributing the observed changes and trends to individual or combinations of causal (forcing) factors. The answer to this problem lies one step deeper in the basic physical, chemical, geological, biological, and social processes that control these planetary-scale changes and long-term trends. The basic processes are often mutually reinforcing or, to the contrary, restraining, and combine to constitute feedback mechanisms that amplify or moderate the response to primary disturbances and forcings.

Prominent among these mechanisms are the coupled variations in atmospheric temperature, water vapor, and clouds that govern radiation transfer through the atmosphere and changes in the global radiant energy budget of the planet. A rise in temperature is accompanied by an increase in atmospheric water vapor and its contribution to the greenhouse effect, thereby amplifying the primary forcing that caused the elevation of temperature in the first place. The role of clouds is much more complex, as different types of clouds can induce opposite net effects on the planetary radiation budget. The principal effect of low-lying, dense, and very bright water clouds is to cool the atmosphere by reducing the amount of solar radiation absorbed by the planet, whereas the presence of relatively thin and semi-transparent ice clouds at high-altitude primarily enhances the absorption of terrestrial infrared radiation and warms up the lower atmosphere. Also important is the role of clouds in moistening and/or drying the upper troposphere, as water vapor in that region of the atmosphere, has a potentially large, but incompletely understood, impact on the greenhouse effect and climate.

The formation of clouds is closely associated with the development of weather systems; purely dynamical changes in atmospheric flow will influence the distribution of cloudiness, the radiative balance of the planet, and rainfall distribution, even without any obvious change in global mean atmospheric temperature or humidity. Much improved knowledge of basic cloud processes and the life cycle of cloud systems is needed to predict how clouds might change in the future as a result of change in the atmospheric circulation and thermal structure. In general, a fundamental objective is the understanding of the relationship between climate change and the frequency/intensity of weather disturbances, which play a disproportionately large role in atmospheric transport and mixing, cloud system development, energy transformation, and precipitation.

The health and primary productivity of marine and terrestrial ecosystems are sensitive to changes in climatic conditions as well as the availability of nutrients and other environmental controls. Productivity is governed by the amount of incident solar radiation, the availability of water and atmospheric carbon dioxide; the stability of temperature within the relatively narrow range suitable for life; and the availability of required nutrients in terrestrial soils, brought from the deep by ocean upwelling, or transported by the atmosphere from another region of the Earth. The primary productivity of the biosphere is one of the principal processes governing the Earth's carbon cycle on annual to decadal time-scales. The changing phenological state and health of plants likewise govern the rate of exchange of CO_2 and water between the atmosphere and vegetation, thus controlling, at the same time, the storage of carbon and the loss of water by terrestrial vegetation. In this respect, vegetation plays a major (moderating) role in the hydrological cycle, surface water storage, run-off, infiltration, and regional hydrologic regimes in general. Similarly, in the ocean, phytoplankton.contribute significantly to spatial variations in CO_2.

From an Earth system perspective, the global carbon cycle is governed by the global distribution of marine and terrestrial ecosystems and the impact of their biological activity on the global environment. In particular, it is essential to relate the intensity of biological activity to the controlling (radiative, meteorological, hydrological, biogeochemical) factors on a global basis, including the cycling of other chemical elements (e.g., nitrogen) that are critical to the development and functioning of ecosystems.. Remote sensing provides the opportunity to gather much of the needed global data on both the distribution of ecosystems and relevant forcing factors, but converting these observations to information on global environmental impact requires sufficient knowledge about basic processes and the function of ecosystems. Process-level knowledge is acquired primarily through *in situ* studies, often in the context of major field campaigns which allow detailedanalysis of key processes and controlling factors.

Likewise, it is essential to understand the global water cycle, both as the central element of atmospheric climate change and a critical environmental factor that influences the other components of the Earth system. In particular, the availability of soil moisture and the transition of frozen soil to thawed conditions have a controlling influence on the productivity of terrestrial ecosystems. Conversely, the phenological progression of vegetation from dormant, to growing, to mature stages, governs the ability of vegetation to draw water from the ground, transfer it to the atmosphere, and thereby influence surface climate and the partitioning of radiant energy between latent and sensible fluxes. The global measurement of soil moisture, snow-water equivalent, freeze-thaw transitions, stage of water in rivers and inland water bodies, and river flow could significantly enhance our knowledge of the global water cycle..

It has been shown beyond doubt that halogenated compounds produced by human industry are the primary cause of global decline in the amount of stratospheric ozone. This includes both the decreases in global ozone amounts and the much larger decreases in high latitude spring observed in the Antarctic and, to a lesser extent, in the Arctic region.. The phenomenon is governed by the complex chemistry of atmospheric ozone, involving numerous chemical species and free radicals, and controlled by climatic conditions that allow very low temperature to form and persist for long periods of time. Conversely, the distribution of ozone and some other absorbing molecules control radiative heating and stratospheric climate (circulation and temperature).

This linkage between chemistry and climate provides opportunities for complex and non-linear interactions. Most importantly, low stratospheric temperatures permit the formation of cloud and aerosol particles, which can have significant implications for both atmospheric chemistry and for radiation. Detailed understanding of the conditions under which these particles form is important if accurate forecasts can be made in an atmosphere with altered temperature distributions. Similarly, changes in the dynamics of the tropopause region could affect the transport of water vapor and other trace gases from the troposphere into the stratosphere and thus affect aerosol formation, chemistry, and radiation in the stratosphere. Understanding how stratospheric water vapor might change in the future requires basic understanding of the dynamics of the tropopause region and troposphere-stratosphere exchange mechanisms. Finally, any change in meteorological activity that drives the stratosphere and affects the stability of the polar vortices will have significant impacts on chemistry, especially the partitioning of chlorine and nitrogen between compounds which are more and less active in ozone depletion. Conversely, atmospheric model simulations show that changes in stratospheric circulation and thermal structure may propagate downwards and affect tropospheric climate. The factors that control the stability of the polar vortices and their relationship with tropospheric circulation must be understood to assess the implications of possible future variations.

Microphysical and chemical processes, as well as atmospheric transport, mixing, and removal, govern the formation of aerosols in the lower troposphere from a variety of surface sources and/or precursor gases, their number and size distribution in the atmosphere, their composition and optical properties, and ultimately their direct effect on the planetary radiation balance. Satellite observations provide the potential to help characterize the global distribution and, to some extent, the properties of aerosol particles in the atmosphere. However, variability in aerosol types, height, chemical composition and optical properties means that satellite observations alone cannot provide all the needed information on aerosols. A variety of observational data from *in situ* sampling, airborne and ground-based optical remote sensing, advanced satellite instruments, and detailed modeling studies of aerosol processes will be needed to understand the relationship between aerosol composition, height distribution, and optical properties under a sufficiently broad range of aerosol types and geophysical conditions. Even more complex cloud-dynamical and microphysical phenomena are initiated by aerosol condensation nuclei which may induce significant changes in the particle size distribution of low-lying clouds and cause indirect climate forcing by altering the optical properties of these clouds. Sufficiently detailed knowledge of the processes by which aerosols affect cloud formation and properties must be obtained on a global scale so that these indirect effects can be realistically represented in models.

The formation, transport and eventual melting of sea-ice at high latitude involve complex ice and water properties, polar weather phenomena, and the oceanic circulation. Over 10-13% of the surface of the ocean, sea-ice acts as an insulating layer that blocks exchanges of water and energy with the atmosphere. The high albedo of raw and snow-covered ice further reduces the absorption of solar radiation and tends to maintain the surface cold, with direct consequences on polar atmosphere stability and weather. The formation of sea-ice is accompanied by the rejection of concentrated brine that increases the salt content of the ocean locally and promotes the sinking of cold, high-salinity surface water to great depth. Conversely, the advection and melting of relatively fresh sea ice lowers the salinity of the ocean and blocks deep water formation, thus inducing a complex coupling between sea ice, deep water formation, and decadal climate variability. The measurement of ocean surface salinity can dramatically increase our knowledge of the conditioning of ocean waters by air-sea interactions and their impact on deep-water formation.

2.4 Consequences of Changes in the Earth System for Human Societies

Statistically meaningful but small changes in the global distribution of Earth system properties, such as mean surface temperature or sea-level pressure, would not draw much attention if we did not foresee that relatively small variations in the global environment can entail changes of much greater significance in regional weather, productivity patterns, water resource availability, and other environmental attributes. We already know, for example, that La Niña climate episodes, manifested by cooling of surface waters in the eastern tropical Pacific ocean by a few degrees Celsius, are associated with more active hurricane seasons in the Atlantic basin, featuring more frequent and generally stronger tropical cyclones than normal years. Conversely, El Niño warm ocean water episodes have dramatic impacts on regional marine productivity and broader climate patterns, including the frequency of Atlantic hurricanes.

There is little doubt that other global climate changes can also induce significant differences in the frequency, duration and intensity of weather disturbances, such as severe storms and rainfall, floods and droughts. In particular, the acceleration of the global water cycle due to warmer temperatures is expected to produce heavier rains and larger water run-off, especially in winter, but also faster evaporation and generally drier conditions in summer, thus amplifying the contrasts between dry and wet seasons, and exacerbating chronic water shortfalls in arid regions. Global climate warming observed during the last few decades appears to have already resulted in a lengthening of the growing season at mid- to high-northern latitudes, and may be contributing to desertification in the sub-tropics (IPCC, 1998). Changes from snowfall to rainfall would also significantly affect the annual patterns of stream flow (higher in winter, earlier peak flow, lower summer flows), which can have dramatic impacts on fisheries as well as irrigation needs.

Sea-level rise, resulting from the thermal expansion of ocean waters and mass loss from continental glaciers and ice sheets, is a gradual but important phenomenon of concern to all coastal countries, especially low-lying atolls. Sea level rise is accompanied by a redistribution of coastal materials, beach erosion, flooding of freshwater wetlands and the invasion of coastal aquifers by salt water. The societal implications of sea level rise are significant. It is estimated that a 0.5 m rise in sea level would cause a loss of about a third of US wetlands (with corresponding loss of the biogeochemical recycling capability and ecosystem goods and services, such as fishery productivity, from such wetlands.

Ecosystems may have difficulty adapting to relatively rapid changes in the physical environment. Climate change is thus becoming an additional stress that may combine with other stresses, e. g. invasion by exotic species or increased frequency and/or extent of fires, to alter drastically the structure and composition of established ecosystems and lead to their impoverishment or ultimate disappearance in favor of a more tolerant ecosystem. An example of a particularly sensitive ecosystem that cannot easily "migrate" to a more favorable region is that of tropical corals, now subject to bleaching and death almost everywhere. Deforestation and other ecosystem disturbances caused by human activities can result in irreversible changes, such as loss of species (biodiversity), and other undesirable effects such as increased erosion, loss of essential nutrients, decreased agricultural productivity, and accelerated rainwater runoff from watersheds. It is vitally important to understand the consequences of such changes for sustained agriculture, forestry, and fisheries and the continued provision of ecosystem goods and services that are valuable to human societies. It will be especially important to understand the controlling factors when sustainable production is successfully achieved while the ecosystem is under pressure from population growth and/or land use change

The growth in human population and the increasing levels of industrial activity, especially in developing countries are likely to combine and lead to dramatically increased gaseous and particulate matter pollution of the atmosphere in some parts of the world (e. g. south and east Asia and Latin America), with attendant consequences for human health and ecosystem productivity. There is evidence that pollutant gases from densely populated regions, notably carbon monoxide, sulfur dioxide and oxides of nitrogen, can be transported over very large distances by the atmospheric circulation, thus causing air quality problems in regions far removed from the sources. It has been recognized recently that the transport of pollutants in the troposphere takes place principally within thin layers that may extend over very long distances. Such long-distance transport creates risks of increased pollution far away from the sources, for instance pollutants from Asian sources over the west coast of the United States. Surface air quality data have given support to such connections Such long range transport is also capable of transporting nutrients over long distances (for example, from the Saharan desert to the subtropical Atlantic Ocean or the Amazon) and thus play an important role in ecosystem productivity and biogeochemical cycling for a broad range of nutrients.

Reductions in stratospheric ozone amounts have been shown to lead to increases in the amount of biologically damaging ultraviolet radiation that reaches the Earth's surface. The harmful effects of UV radiation on humans include skin cancer, cataracts, and immune system suppression. UV radiation can also have significant impacts on ecosystems, especially the phytoplankton that are a critical element in the oceanic food chain. Effects of UV increases are of special interest at high latitudes where the largest decreases in ozone have taken place.

2.5 Prediction of Future Changes in the Earth Climate and Global Environment

The overarching purpose of Earth system science is to develop the knowledge basis for predicting future changes in the coupled physical, chemical, geological, biological, and social state of the Earth and assessing the risks associated with such changes. Of particular interest are changes in physical climate on the time scale of a human generation, e. g. changes in the composition and chemistry of the atmosphere, and changes in biogeochemical cycles and primary productivity. It is clear that to predict the long-term evolution of the Earth system, a good understanding of the way that humans will interact with the environment must be obtained and represented in the models used for simulations.

A first step towards predicting the future of the Earth system is building a capability to simulate realistically the present state and short-term variations of the global environment. This includes defining accurate and realistic representations of all relevant forcing factors and their role in the system, and the physical, chemical, geological, and biological processes involved, including especially the processes which couple the different components of the system: the global atmosphere; the world oceans; land and sea ice; marine and terrestrial ecosystems; and the Earth's landscapes and surface geology. The only practical strategy for such a complex task is to develop predictive skills, focusing necessarily on suitably defined sub-systems of the complete Earth system for verification against observations.

Frequent experimental data assimilation and prediction cycles, made possible by the daily acquisition of global atmospheric, oceanic, and surface observations, are instrumental in verifying and improving the representation (prediction) of realistic weather and weather-related phenomena in climate models. On longer time scales, realistic representation of atmosphere-land hydrology and atmosphere-ocean interactions, as well as the full three-dimensional nature of the ocean, become essential. Experimental predictions of significant interannual climate fluctuations, for example ENSO phenomena clearly require information on the physical state of the oceans. Simulation of transport, mixing and transformations of trace gases and aerosols in the Earth’s atmosphere is an attractive proposition whenever suitable environmental and meteorological data are available to verify model predictions. Predictions based on atmospheric chemistry or biogeochemical cycling models may be tested against the current distributions of relevant compounds in the Earth's atmosphere, oceans, land, and biosphere. Ecological research is striving to acquire the same type of information on marine and terrestrial ecosystem dynamics to test model simulations of the recovery of these ecosystems from known disturbances or stresses.

Predictive models can similarly be used in a retrospective mode to simulate past changes for the purpose of testing hypotheses about the possible causes of these changes and verifying the models' capability to reproduce the full range of observed variability. The latter is especially important to gauge our capability to assess the risk for rapid changes and possible surprises in the evolution of the Earth system. The use of mathematical analogs to simulate past changes, that are documented directly in the historical record or indirectly by various existing paleoclimatic indicators, is also a powerful means to identify key linkages between the components of the Earth system.

The objective, however, is to build on the confidence gained in simulating current or past environmental conditions and apply these skills to the prediction of future long-term changes. Such predictions are usually intended to assess the potential consequences of various assumed scenarios for the future evolution of relevant forcing factors: emissions of active chemical compounds and greenhouse gases from various sources, changes in the global cycles of carbon, nitrogen, and other important elements, changes in land use and water management, population growth, economic development, etc. It is important that the modeling tools used for prediction have the capability, including spatial resolution, needed to address regional impacts of predicted global changes.

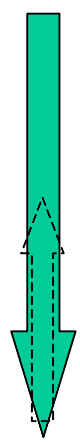
3. SCIENCE PRIORITY CRITERIA

The Earth system science issues outlined above are remarkable for the diversity of topics, the complexity of the interactions, the multiplicity of spatial scales (from microscopic to global), and the range of time periods (conceivably, from minutes to millions of years). A great number of scientific questions have been posed by the nation through NRC reports (e. g. *Global Environmental Change: Research Pathways for the Next Decade,* NRC, 1999a) and the USGCRP. In fact, the focused attention placed on global change research over the last decade has energized the Earth sciences and greatly enhanced both our understanding of Earth system processes and the range of new scientific questions to be addressed. Investigating the full range of these scientific questions exceeds the capabilities allowed by current resources. No agency or even group of USGCRP partner agencies has the means to address all the important scientific questions posed within the breadth of Earth system science. This makes the issue of program prioritization all the more critical. Optimum return from NASA's investments in Earth observations and research, measured in terms of objective information and answers provided to issues relevant to society, will be obtained when scientific value is the leading factor for prioritization.

Establishing research priorities becomes a major challenge when priorities cross a number of different disciplines, each embracing a large set of scientific questions. The challenge facing the ESE is to balance competing demands in the face of limited resources and chart a program that addresses the most important and tractable scientific questions and allows optimal use of NASA's unique capabilities for global observation, data acquisition and analysis, and basic research. To this end, choices need to be made between many projects, all of which are important, timely, and ready to succeed. Most significant from a strategic perspective are the choices between different but equally promising candidate space flight missions or measurement systems.

Thus, NASA’s selection of priorities involves both scientific needs and implementation realities. Scientific considerations are paramount and start the prioritization process. These considerations determine what science questions, and ultimately which research projects (modeling, observations, process studies), should be pursued. Purely scientific considerations are followed by considerations of science-related context (e.g., benefit to society, mandated programs), followed in turn by implementation considerations. The latter, such as technology readiness, tend to impact the order in which science projects are pursued and the final shape they may take. These practical considerations often result in some feedback and iteration of project selection.

Science Priority Criteria



Science Return

Benefit to Society

Mandated Program

Appropriate for NASA

Partnership Opportunity

Technology Readiness

Program Balance

Cost/Budget Context

Implementation Priority Criteria

The list of criteria is not ordered by importance in all cases; rather, it is presented in a logical order of procession as project concepts are conceived and matured. It is worth noting that the details of applying these criteria may vary, especially given the nature of the question being investigated and the mission potentially being initiated. These criteria are described in the following paragraphs.

Scientific Return

The scientific return of research activities, such as discussed in the plan, is judged in term of the perceived significance of the scientific problem being addressed in the grand scheme of Earth system science, and anticipated advances toward providing definitive answer(s). Scientific return is often high for innovative investigations that break into heretofore unexplored scientific territory. In other instances, major scientific advances are achieved only through systematic analysis of vast bodies of observational evidence, as is often the case in the study of complex systems like the Earth. Best scientific return is generally obtained when research and observing program initiatives are conceived and designed to address specific science issues or questions. To ensure full scientific return, the ESE recognizes the need for a balanced research program that provides not only unique space-based and airborne observational capabilities, but also the means to analyze the data, compare to surface-based measurements and state-of-the-art models, and conduct end-to-end research projects that can deliver conclusive answers to specific Earth system science problems.

Finally, scientific priority also stems from the logical progression in approaching a complex scientific problem. Identifying the significant elements of variability in the Earth system and trends in forcing factors provides a necessary foundation for deeper insight in response mechanisms. Likewise, investigation of the consequences and the development of robust prediction methods require a priori knowledge of the operative processes. The program implemented by the ESE will represent an appropriate balance between the different steps of this progression. The potential for amplification of the response is an element of this choice (e. g. the positive feedback associated with changes in the distribution of atmospheric water vapor). As regards climate change assessments, for example, the largest sources of uncertainty have been identified by the Intergovernmental Panel on Climate Change (IPCC, 1996).

Benefit to Society

In addition to scientific merit, one of NASA's strategic goals is to develop useful information, products, and capabilities for society. NASA research is expected to contribute to society in several ways. As governments, businesses, and individuals make decisions about their future plans, ***scientific information*** about the environment and potential changes will be an important element of the decision process. NASA science should contribute to the flow of this information, especially in issues such as climate variations and trends, ozone depletion, and the state of the biosphere.

The observational ***data products*** obtained primarily for scientific purposes can also be used for the conduct of current operations by individuals, businesses, state and local agencies, land use planners, and resource managers, among others. Not only must the data be made available to these constituencies in an appropriate form and a timely fashion, but a data system must be available that facilitates the sharing of this information. An element of choice in selecting research programs is the potential for continuing infusion of relevant data for applications purposes.

Experimental observation and modeling capabilities developed by NASA for scientific purposes can be used by operational agencies for practical applications. There is particular interest in scientific investigations that could enhance the accuracy and range of ***weather forecasts***, e. g. through the introduction of new data sources, or improvements in predictive models and data assimilation methods. Close cooperation with NOAA and other forecasting agencies is desired to assure that the results of NASA science are incorporated into operational systems and products.

Mandated Programs

A special case of research programs beneficial to society, mandated activities include legislative requirements to maintain a research, monitoring, and technology development program related to the surveillance of atmospheric ozone for atmospheric chemistry research and monitoring, as specified by NASA's Authorization Act and the Clean Air Act. NASA is also required to report to Congress and the Environmental Protection Agency every third year on the status of knowledge of atmospheric ozone and the abundance of ozone-depleting substances in the atmosphere. More recently, the Enterprise has been directed to increase its research effort on the global carbon cycle. Finally Congressional directions, received through the budgeting process, must also be met.

Appropriate for NASA

NASA shares with other USGCRP partners an interest in fundamental studies of the basic processes that govern the Earth system, diagnostic studies of recent and past data records, and model simulations/predictions of global changes. At the same time, effective use of resources requires that the ESE's science strategy be focused on research projects that allow optimal use of NASA's unique capabilities. Compared to the range of investigations embraced by the entire USGCRP, NASA's Earth science program emphasizes measuring changes in forcing parameters, and documenting the natural variability of the Earth system and responses to forcings, especially through space-based measurements that can provide global coverage, high spatial resolution, and/or temporal resolution, in combinations which cannot be achieved by conventional observational networks.

The *Research Pathways* report (NRC, 1999a) formulated a wide range of research imperatives and scientific questions that require investigation across the field of Earth system science. Choosing among all potentially important research questions is a judgment of scientific value. In the context of NASA's Earth science research program, the principal scientific priority criteria are the spatial scale, temporal duration, and magnitude of the phenomena being investigated, as well as anticipated return in term of reducing the uncertainty on potential changes in the Earth system.

Research questions that address Earth system dynamics at ***large regional to global scales*** are those of greatest interest for the ESE. Questions that involve smaller scale changes that have the potential to be of global significance if aggregated over a sufficiently large number of areas, are also relevant to ESE. This is particularly true for regions where only limited conventional (non-space) observations are available (e. g. the atmosphere over the open ocean and polar regions; continental ice sheets). For example, ESE's atmospheric chemistry research has been focused on global scale chemical processes rather than local air quality (which is typically the responsibility of regulatory environmental agencies).

Likewise preference is given to the study of phenomena and processes that may induce lasting changes in the Earth system, typically ***seasonal and longer period responses***, as well as changes that are irreversible in the foreseeable future. Understanding and predicting fast processes (e. g. the development of weather systems, trace gas emissions) may be essential in order to quantify longer-term average impacts. While forecasting individual environmental phenomena is not a primary ESE objective, further developing experimental prediction of specific events (e. g. weather disturbances) that can be verified by observation is a fundamental research tool for understanding changes in climate and the global environment (e. g. mean displacement in storm tracks). At the process level, priority is given to those processes that have the potential to induce ***large impacts*** and/or are the root of large uncertainty in the overall response of the Earth system.

NASA has a very strong commitment to the use of its observational data in scientific research, and invests in the development of models and global data assimilation systems that can be used for the analysis and interpretation of observations from NASA programs and other relevant observing networks, as well as for the development of improved forecasting capability related to answering the questions posed in this plan. NASA's earth science research program also has a robust sub-orbital component, which is focused on improving our understanding of processes needed to understand, interpret, and model remotely sensed observations, as well as to contribute to the calibration and validation of the space-based observations. Innovative combinations of observing instruments and platforms are used in this component of the program.

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Partnership Opportunity

The ESE research program is conducted within a larger national and international context. This implies both opportunities for task-sharing with partner agencies, and the responsibility to seek optimal coordination of mutually supportive programs of these national and international partners. In particular, NASA has been actively seeking the cooperation of operational agencies in the US (through the National Polar-Orbiting Operational Environmental Satellite System, NPOESS) and elsewhere to ensure the long-term continuity of key environmental measurements in the long term. To achieve this goal, NASA will promote the convergence of the operational observation requirements of partner agencies with ESE research data needs for systematic observations, share the cost of new developments, and develop precursor instruments and spacecraft technologies for future operational application missions. NASA will also encourage the continuing involvement of scientific investigators in the calibration and validation of operational measurements, the development of more advanced information retrieval algorithms, and the analysis of operational data records. From this perspective, the potential for serving operational needs or commercial applications is a priority criterion for ESE programs, since such applications imply the potential for cooperation with relevant government agencies or data purchase from commercial sources.

Interagency and international partnerships are also important methods for maximizing the scientific value of any research activity while minimizing costs. The need for partnerships in process-oriented field measurement activities is crucial, especially when investigators' access to particular regions of scientific interest is needed. For space-based measurements, partnerships provide the opportunity for leveraging additional contributions onto those that would be made by NASA, and allow for benefiting from the technological and scientific skills resident in other agencies and countries, as well as access to information needed for validation under a broad range of biological and geophysical conditions. Partnership opportunities will typically be encouraged in all relevant solicitations as long as they are consistent with national policy objectives such as export control of sensitive technology. Commercial partnerships also provide the opportunity for NASA to obtain needed data or services, and NASA has committed to working with the private sector to avoid duplicating capability that already exists in it.

Technology Readiness

For observation projects in particular, a key criterion in determining the timing and order of selection is the readiness of the relevant technology. In some cases, as with soil moisture measurements, additional technological investments were required over the past and current years in order to demonstrate the possibility of making this measurement from space. For instance, lidar wind measurements were possible a decade ago, but only at an unacceptable cost for development and operations. Recent and ongoing work indicates the potential for design of a space-based system at a cost comparable to current programs, and perhaps even implementation as a commercial data purchase. NASA implements technology development programs relevant to each stage of the instrument maturation process (e.g., components, instrument design, flight demonstration). Parallel programs in spacecraft and information technologies are pursued to assure overall mission feasibility.

Program Balance

The hallmark of NASA's Earth science program is the synergy between different classes of observations, basic research, modeling, and data analysis, as well as field and laboratory studies. In particular, when engaging in pioneering research about complex scientific issues, the ESE recognizes the need for complementary remote sensing and in situ measurements. Nonetheless, the strategic decisions that define the ESE program in the long term are those which affect the space flight mission element, involving the longest lead-time and largest investment of resources. From both a programmatic and a scientific research strategy perspective, the ESE distinguishes three types of space flight missions: systematic observation missions, exploratory missions, and operational precursor or technology demonstration missions. The identification of these categories represents a significant departure from the original architecture of the Earth Observing System, which combined studying basic processes, assembling long-term measurement records, and introducing innovative measurement techniques. The distinction between these classes of missions facilitates a sharper definition of primary mission requirements, and clearer selection criteria, ultimately leading to a shorter development cycle and more cost-effective implementation. Priority criteria will be considered separately for the research and analysis program and the three categories of missions.

Basic Research and Data Analysis

The intellectual capital for both the planning and exploitation of Earth system observations is vested in an robust research and analysis program. Research and analysis is the conceptual source of Earth system science questions, and strategies to address them. The research program is at the origin of new scientific ideas and emerging research approaches, supports the early development of innovative observing techniques (including both instruments and the linkage of instruments with platforms) and processing algorithms, organizes field tests, and generally charts the path for scientific and engineering developments that enable future advances. It assures the linkage between global satellite observations, ground-, aircraft- and balloon-based observations, including those used for studies of long-term system evolution and shorter-term process-oriented studies, and the computational models used to provide both a framework for interpretation of observations and a tool for prediction. Through focused calibration/validation activities, it helps assure the development of consistent, integrated, and well calibrated data sets, especially those that involve multiple instruments, observational platforms, and observing techniques. The ESE actively supports the scientific use of such multi-instrument/multi-platform data sets for looking at long-term system evolution, and such use frequently serves as the most stringent test of the quality of a scientific data set. The existence of a close tie between research and data-set oriented activities provides the critical "feedback loop" that assures continued focus on maintaining the highest quality data sets possible over long time periods.

Altogether, the research and analysis program brings fundamental research to bear on key Earth science issues, and lays the interdisciplinary groundwork for linking these research efforts. As a general rule, all NASA Earth science research and analysis projects are implemented through a competitive selection process based on responses to solicitations issued by NASA (Announcements of Opportunity, NASA Research Announcements, and Cooperative Agreement Notices) and a scientific peer review.

Systematic Measurements

The need for long-term continuity of critical Earth observations has been repeatedly emphasized by the global change research community. Systematic measurements of key environmental variables are essential to specify changes in forcings caused by factors outside the Earth system (e. g. changes in incident solar radiation) and to document the behavior of the major components of the total Earth system. Following the recommendation of the *Research Pathways* report (NRC, 1999a): "Priority must be given to identifying and obtaining accurate data on key variables carefully selected in view of the most critical scientific questions and practically feasible measurement capabilities".

Systematic is not necessarily synonymous with continuous measurement. Gaps in systematic measurement time series may be tolerable for scientific investigations when short-term natural variability or calibration uncertainties between successive discontinuous records do not mask significant long-term trends. In principle, ESE plans for systematic observations aim for measurement continuity, based on best estimates of observing system lifetimes and time for replacement. On the other hand, the ESE's mission implementation plan does not provide for instantaneous (in-orbit) replacements in case of premature sensor or spacecraft failure. Overlapping measurement records from successive sensors are required, however, when no ground-based observation can provide an independent calibration standard (e. g. solar irradiance). It is essential that requirements for systematic observation programs be reviewed and focused on a minimum set of essential measurements.

A particular challenge for NASA and other agencies occurs when systematic observations are transitioned from those obtained in a research-oriented program to those that will be obtained in an operationally-oriented one (NRC, 2000). Such a transition is expected to take place over the course of this decade for a number of environmental parameters, especially given the planned initiation of NPOESS near the end of the decade. In particular, assuring the ability of data from operational entities for studies of long-term global change questions requires the very accurate knowledge of absolute and relative calibration of relevant instruments, the upgrading of retrieval algorithms (including those that may make use of ancillary data sets not normally used in the operational algorithms), and the periodic reprocessing of data sets needed to assure consistency for the construction of the required multi-instrument/multi-platform data sets. ESE expects to work closely with NPOESS to facilitate such developments, and where need is demonstrated, to support such activities through this transition period so that the ability of the earth science research community to answer the questions posed in this plan (especially those of long-term variability) can be sustained.

Exploratory Measurements

Exploratory missions which can yield new scientific breakthroughs must be a significant component of the ESE's program, in conformity with the strategic mission of NASA to promote research and development. Each exploratory satellite project is expected to be a one-time mission that can deliver conclusive scientific results addressing a focused set of scientific questions. In some cases, this may involve measuring several related parameters to allow closure tests to be carried out. In other cases, an exploratory mission may focus on a single pioneering measurement that opens a new window on the behavior of the Earth system. Included in this class of missions are small, university-led missions which seek to train the next generation of scientists at the same time scientific information is obtained. No commitment for long-term measurement is made with this class of mission, although it is possible that the results of an exploratory project could lead to introducing a new systematic measurement or transition to an operational application program.

Operational Precursor & Technology Demonstration Missions

The ESE recognizes that requirements for more comprehensive and accurate measurements place increasing pressure on operational environmental agencies and require major upgrades of existing operational observing systems. In order to enable such advances, NASA will invest in innovative sensor technologies and develop more cost-effective versions of its pioneer scientific instruments that can be used effectively by operational agencies. The plan identifies several operational precursor or "bridging" missions that will lead to future operational deployment in low Earth orbit or geostationary orbit during the next decade, principally within the framework of the NPOESS and GOES programs. Active participation of operational agencies in the definition and development of the new systems, and their commitment to transition to operational status, are essential for the success of such operational precursor developments. In this regard, the determination of the partner agency to continue a new observation when technological readiness is demonstrated is a major element of choice in NASA's decision to invest in operational precursor missions. Continued close working relationships between ESE and its partners are clearly needed to drive initiatives in this area.

Data Management and Distribution

The satellite, process study, and modeling and data assimilation programs of ESE have the capacity to produce unprecedented amounts of data, the value of which is only maximized with their full use by the international Earth Science research and applications communities. This volume of data, together with the diversity of the user community, provide a significant challenge to the enterprise because of the need to assure both prompt and easy access by users with varying degrees of knowledge and expertise and the ability to maintain the quality of the data over long time periods. A successful data and information systems and services program includes both planning for scientific data quality refinement, allowing for periodic reprocessing and data stewardship, providing for archive integrity and continual infusion of new technology (including storage media). Further, it is recognized that Earth science research will use more than just ESE data (for instance, observations from operational space- and ground-based environmental measurement systems) so data systems that are interoperable with those of other providers of critical Earth Science data are needed.

To assure this availability, ESE has made a major commitment to data processing, archival, storage, and access, and expects to continue this in the future. Through this commitment, the enterprise endeavors to make data available to the science and applications research communities at minimal costs. The method of data system implementation is expected to evolve, however. Prior plans, focused on logically centralized computing and storage systems developed based on earlier technology, are now being followed by those that take full advantage of more recent developments in computing technology and networking to provide for a framework linking the user to products and services within more heterogeneous distributed data systems. An operative principle in the ESE’s treatment of its data is to assure continual involvement of interested scientists who have a scientific stake in the data being managed and archived.

Completing the Cycle – from Scientific Results to Answers to Questions

The ESE research program, including its observational and modeling component, provides a vast amount of scientific information of various types – basic knowledge of processes, large observational data sets, model calculations being among them. An important activity of the ESE research and analysis program is to help the scientific community digest and synthesize the results, and advance from an increase in specialized scientific knowledge to well-documented answers to the broader questions posed in this plan. NASA will actively support the development and implementation of an appropriate process to "complete the cycle" in which questions are formulated, scientific studies are carried out, specific answers are developed to the extent possible; organization of and/or participation in specific assessments on a periodic basis will be used to evaluate progress towards resolving the science questions outlined in section 4. NASA will also re-evaluate its overall strategy periodically and involve the scientific community in the re-evaluation process.

The nature of the scientific enterprise is that initial results will be reported through the peer-reviewed scientific literature and presented at scientific meetings. The sheer volume of scientific findings and, in many cases, the diversity of ideas, imply that a synthesis effort is needed to communicate the information usefully outside the scientific community. Several pathways exists to produce such syntheses. The assessment process, in which groups of scientists work to synthesize their knowledge in a particular area, is perhaps the best established means to make the connection between research results and the answers sought by the sponsors of research. In such assessments, the scientific community comes together to answer not only questions such as “What do we know?” but also, and perhaps equally importantly, “How well do we know what we think we know?”

International assessments, such as the ozone change assessments carried out for the World Meteorological Organization and the United Nations Environment Programme or the climate change assessments carried out for the Intergovernmental Panel on Climate Change have a long history of accomplishment and continue to play a seminal role in the development of the relevant disciplines. Other, more specialized, assessments are undertaken to resolve (or progress toward resolution of) a specific scientific issue. The recent report from the National Research Council on *Reconciling Observations of Global Temperature Change* (NRC, 1999b) is a noteworthy example of such a study. NASA will facilitate such consultations of the Earth science community to evaluate the effectiveness of its research strategy.

Through the US Global Change Research Program, NASA is strongly engaged in the National Assessments on Climate Change process. These assessments have both regional and sectoral foci, and serve to bring together not only the scientific research community, but also users within federal, state, and local governments, as well as regional agencies, the private sector, and non-governmental organizations. The assessments provide a particularly critical way to try to provide clear answers to climate variability, consequences, and prediction issues at the spatial and temporal scales that matter directly to environmental decision-makers.

NASA will help enable a strong participation of the ESE research community in assessment activities and values their involvement, as well as the use of ESE data in such assessments. In all cases, the aim of the assessment is to express the outcome of the scientific synthesis effort in a form that is useful to decision-makers in government, industry, and the broader society. The evolving needs of these users, and the outcome of the assessments themselves, serve to refine the scientific questions, thus completing the cycle and providing new directions for research.

Cost/Budget Context

In the end, the set of research projects of all types must be mapped into the overall budget context constraining NASA’s Earth Science Enterprise. This is not a fixed parameter; the budget level itself is partly a function of the scientific rationale and societal benefit that a balanced Earth Science program can provide. Once established, the negotiated (or anticipated) budget envelope becomes a criterion that may drive an iteration for many projects back up the criterion ladder to some level.

4. NASA EARTH SCIENCE RESEARCH PRIORITIES

The five fundamental science questions define a logical progression in the study of global change, but each question covers a range of topics too broad to serve as a guide for program implementation. For this purpose, more specific research questions need to be formulated and prioritized. These second-tier questions, summarized in Table 4.1, are discussed in significantly greater detail in the subsequent chapters of the plan and ranked within each of the five fundamental questions on the basis of the criteria enunciated in section 3, principally scientific return and benefit to society. The major factors to be considered in prioritizing the questions, discussed in more detail for each question, are the amplitude of the impact of the particular variations, forcings, or responses on the Earth system, the likelihood of a breakthrough; the lead time for reaching a conclusive answer or developing a new prediction capability; and the significance of potential consequences or applications for society. When it comes to implementing missions, other criteria, such as technology readiness and partnership opportunities will become increasingly important, as will the cost/budget context in which mission development can take place and program balance across the enterprise.

As noted earlier, the details of the implementation of the criteria may vary for different types of missions. For example, in implementing systematic missions, timeliness is likely to be a much more significant driver than in the case of exploratory missions, as continuity of a particular environmental parameter may be at stake. Similarly, partnership arrangements will be critical in formulating potential operational precursor missions, but may not be a driving issue in the formulation of exploratory missions, except to the extent to which partner contributions allow for improved science relative to NASA's financial commitment. The announcement of opportunity (AO) or other procurement vehicle that might be used for a particular mission solicitation, will reflect the criteria and their relative priorities.

Nonetheless, it should be emphasized that the Earth is a strongly interactive system and that conclusive results cannot be expected by either focusing exclusively on a single component (e.g., variability) at a time or addressing these in a purely sequential manner; progress must be made in all areas, although the balance of resources applied towards individual components in the program may vary over time. Recognizing this need for progress in these multiple areas he five fundamental science questions are not prioritized. Indeed, progress in all five research areas is critical if we are to develop a predictive capability for the Earth system based on robust scientific understanding of natural variability, human forcings, and responses.

The research expertise that NASA brings to answering the questions posed in this plan is strongest in the disciplines that individually and collectively constitute the field of Earth system science, as well as several areas underlying science (e.g., physics, chemistry, ecology, applied mathematics and computing, data and information systems). It is clear, however, that developing answers to all of these questions (especially those in the areas of consequences, as well as several areas of forcing, such as land use change) will require a broad range of scientific expertise, including that of the social sciences, with which NASA's interactions have historically been more limited. Closer ties between NASA and the social science research community are being developed through NASA's Land Cover and Land Use Program as well as NASA's applications efforts (described in the ACE plan), and the development of interactions between the respective research communities will be encouraged. NASA will also draw on the social science research expertise available through other agencies of the USGCRP.

In posing the specific questions, key parameters for which observations are required will be identified and summarized in tables (one table for each major question area). It is important to recognize that not all the data sets needed for the key parameters must be derived from NASA projects. Indeed, many come from operational activities of other agencies, and include both space-based and those from other (ground-, ocean-, and balloon-based) platforms, while others may come from research networks provided by other agencies. Included in the tables are lists of parameters tied back to the most relevant question, details of implementation, and considerations associated with several of the criteria described in the previous section (technical readiness, partnership potential, including that for transition to operational agencies).

Table 4.1: Hierarchy of Science Questions

Overall: ***How is the Earth changing and what are the consequences for life on Earth?***

- ***How is the global Earth system changing?(Variability)***
  - How are global precipitation, evaporation, and the cycling of water changing?
  - How is the global ocean circulation varying on interannual, decadal, and longer time scales?
  - How are global ecosystems changing?
  - How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?
  - What changes are occurring in the mass of the Earth's ice cover?
  - What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes**?**

- ***What are the primary forcings of the Earth system? (Forcing)***
  - What trends in atmospheric constituents and solar radiation are driving global climate?
  - What changes are occurring in global land cover and land use, and what are their causes?
  - How is the Earth's surface being transformed and how can such information be used to predict future changes?

- ***How does the Earth system respond to natural and human-induced changes?(Response)***
  - What are the effects of clouds and surface hydrologic processes on Earth's climate?
  - How do ecosystems respond to and affect global environmental change and the carbon cycle?
  - How can climate variations induce changes in the global ocean circulation?
  - How do stratospheric trace constituents respond to change in climate and atmospheric composition?
  - How is global sea level affected by climate change?
  - What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?

- ***What are the consequences of change in the Earth system for human civilization?(Consequences)***
  - How are variations in local weather, precipitation and water resources related to global climate variation?
  - What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
  - What are the consequences of climate and sea level changes and increased human activities on coastal regions?

- ***How well can we predict future changes to the Earth system?(Prediction)***
  - How well can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?
  - How well can transient climate variations be understood and predicted?
  - How well can can long-term climatic trends be assessed or predicted?
  - How well can future atmospheric chemical impacts on ozone and climate be predicted?
  - How well can cycling of carbon through the Earth system be modeled, and how reliable are predicted future atmospheric concentrations of carbon dioxide and methane by these models?

4.1 Earth System Variability and Trends

Systematic measurements provide the fundamental knowledge basis for diagnostic studies of Earth system changes, as well as investigating the mechanisms underlying these changes (see 4.3 below). The *Research Pathways* report (NRC, 1999a) defined the goal of global change research as that of "obtaining accurate [observational] data on key variables carefully selected in view of the most critical scientific questions and practically feasible measurement capabilities". The objective is to identify significant changes in the states of the principal components of the Earth system: the atmosphere and oceans, terrestrial and marine ecosystems, atmospheric chemistry, ice sheets, and the Earth's topographic surface. To this end, the observational strategy will be focused on a limited set of independent properties that each characterize an important component of the system. In implementing observations needed for systematic measurements, a focus on long-term precision, calibration information and validation over the lifetime of the mission are critical if separate data sets are to be combined into the multi-instrument-multi-platform data sets necessary for quantitative studies of long-term global change.

The study of the Earth's interior plays a supporting role in the research strategy, as the interactions of Earth's internal processes with the other four components are less significant on relatively short (10-100 year) time-scales. Systematic observations of solid Earth parameters provide a foundation for many Earth system science investigations, notably the precise shape of the Earth's surface, the gravity field and its variations, and the geodetic reference frame for navigation and GPS-based remote sensing systems.

As noted in the previous section, not all required observational parameters need come from NASA projects. This is especially true for systematic measurements, in which observations of global meteorological and oceanic parameters from the space-based and in situ measurement network of operational agencies are the primary data sets for some parameters. For others, plans have already begun to transition such operations from research-oriented organizations, such as NASA, to operationally-oriented ones, such as NPOESS. Observational parameters for which systematic measurements are most needed are summarized in Table 4.2.

(1) **How are global precipitation, evaporation, and the cycling of water changing?** A statistically meaningful but relatively small rise in global mean temperature (with significant regional differences) has been observed at the surface of the Earth during the last century, particularly the last two decades. Surface warming implies a rise in the temperature of all or part of the atmospheric column, an increase in atmospheric water content, and changes in atmospheric circulation that are manifested by a global pattern of warming and cooling. Such changes would not draw much attention if we did not foresee that relatively small variations in the global environment can entail changes of much greater significance in regional weather, ecosystem productivity, water resource availability, and other essential attributes of the environment. The unambiguous determination of long-term changes in the cycling of water through the atmosphere in the presence of significant shorter-term variations (e.g., seasonal, interannual, including that associated with quasi-periodic phenomena such as El Niño and the Quasi-Biennial Oscillation) presents a challenge to both the measurement approaches used to provide the needed record and the statistical approaches used to try to establish significance.

Atmospheric temperature implicitly determines the large-scale atmospheric flow, including dynamical instabilities that are at the origin of weather phenomena. ***Atmospheric water vapor*** is the principal vehicle of the atmospheric energy that drives the development of weather systems and the source of precipitation. Further, water vapor is a strong absorber of terrestrial radiation; increased atmospheric moisture associated with warmer air has a powerful amplifying impact (positive feedback) on the greenhouse effect. Global temperature and moisture profile measurements are obtained routinely by operational environmental satellites, but the existing operational measurements do not provide the accuracy and consistency required for climate research. NASA investments in advanced sensor technology offer several alternative means (at various stages of technological readiness) to fulfill these scientific requirements. Improved observations will also be of direct benefit for weather forecasting applications.

Global precipitation is the principal indicator of the rate of global water cycle, and can also be used effectively as an input for numerical weather forecasting. Together, the atmospheric water content and global precipitation rate determine the residence time of water in the atmosphere. Precipitation data, obtained routinely by a worldwide network of land-based rain gauges, show evidence of increasing rainfall rates in some regions. In other regions, notably oceanic regions in the tropics, knowledge of precipitation rates has been poor due to the limited observational base. Clearly, the existence of a global trend can only be established on the basis of global rainfall observations. Space-based global observations have been significantly improved by the on-going Tropical Rainfall Measuring Mission and have now reached the degree of reliability needed for systematic measurement.

Changes in s***oil moisture*** over continents have a major impact on terrestrial life and human needs, as precipitation and evaporation govern the runoff of rainfall to the river system, the replenishment of water resources, and the amount of soil moisture available for plant growth. Conversely, soil moisture is a controlling factor of evaporation from the land surface (or plant-mediated evapotranspiration), and the principal indicator of large-scale changes in surficial water reserves. Changes in surficial soil moisture or "soil wetness" affect the dielectric properties of the ground and can be detected remotely by active or passive microwave measurements. Before surface soil moisture can be considered as ready for systematic space-based measurement, it should be successfully demonstrated. NASA will coordinate with all interested agencies in investigating soil moisture measurements and their potential implementation

(2) **How is the global ocean circulation varying on interannual, decadal, and longer time scales?** The circulation of the Earth's oceans is, together with the atmospheric circulation, the mechanism by which the Earth redistributes to the whole planet the excess energy received in the tropics from the Sun. The ocean's enormous capacity for temporarily or permanent storage of heat is a major stabilizing factor of climate. On the other hand, changes in ocean circulation would have significant impacts on global climate. The rate and extent to which the oceans can take up excess energy absorbed by the planet will place a limit on atmospheric heating and climate warming. The ocean circulation also controls marine productivity and modulates the global biogeochemical cycles (notably, the global carbon cycle).

Sea surface temperature is the principal governing parameter of air-sea interaction and a primary indicator of global climate change. The ***extent of sea-ice*** over polar oceans is also a sensitive indicator of climate change, as the annual cycling of the ice cover is determined by a finely tuned balance between radiant heat loss, heat exchanges with the ocean and atmosphere, and the absorption of solar radiation during summer (the latter being strongly dependent upon the rapidly changing optical properties of dry or melting snow and ice). Recent observational evidence indicates not only a significant decreasing trend in the extent of sea ice over the Arctic ocean, but also a decrease in mean sea-ice thickness. The permanent disappearance of summer sea ice in the Arctic is a distinct possibility under plausible climate warming scenarios, and would have a major amplifying effect on global warming at high northern latitudes. Both sea surface temperature and the extent of sea ice are routinely determined by operational observing systems.

Knowledge acquired in the past about ***ocean currents*** and ***sea level*** was derived from *in situ* oceanographic and tide gauge observations available from a limited set of coastal stations or oceanographic cruises. Only space-based observation can provide the global coverage, spatial resolution, and sampling frequency necessary to capture the full range of variability in the global ocean circulation. Space-based measurements of the height of the ocean surface, relative to the reference surface of the Earth gravity field, and of the friction created by ocean surface winds provide first-order information on the ocean circulation. Altimetry also reveals changes in the sub-surface temperature structure and heat content of the ocean, as was observed in the tropical Pacific before the inception of the 1997-98 El Niño event, thus allowing reliable prediction of this climate event.

Accurate knowledge of the Earth's ***gravity field*** and ***the Earth's center of mass*** is also necessary to translate the raw satellite altimetry data into useful dynamic information (height above the reference surface for gravitational potential or "geoid"). New observing techniques being developed now have the potential to raise our knowledge of the geoid to a new level of accuracy, comparable to the precision of altimetric measurements. In the future, it is anticipated that further technical advances will enable detecting transient changes in the Earth gravity field, effectively measuring the gravitational signature of changes in mass distribution at the surface of the planet. Such gravity measurements will enable mapping the time-dependent distribution of water masses (in effect ocean bottom pressure) and learn directly about total ocean transport.

(3) **How are global ecosystems changing?** Variations and trends in the productivity, composition, and health of terrestrial and marine ecosystems are a significant aspect of Earth system variability. In addition to the production of food and fiber, ecosystems govern the changes in the Earth's biogeochemical cycles, especially the carbon cycle, and modulate the cycling of water over land through changes in storage capacity and evapotranspiration. Peaks in marine primary productivity (blooms) usually occur when oceanic motions bring nutrient-rich waters into the well-lit upper oceans. Such events often dominate the downward flux of organic carbon. Terrestrial primary productivity varies more predictably with the seasons over much of the Earth's land surface, initiating photosynthesis and growth after the thawing of frozen soils or with the onset of a rainy season, peaking when environmental conditions are optimal, and declining when temperatures drop below freezing or with the onset of seasonal drought. Annual primary productivity does vary significantly from one year to the next in response to a variety of environmental factors, such as changes in nutrient supply and extreme or variable weather events, as well as year-to-year meteorological variability, including that associated with quasi-periodic phenomena such as El Niño. Satellite observations provide the only means to obtain a global view of the Earth's ecosystems, their spatial distribution, extent, and temporal dynamics, and to estimate changes in ***primary productivity***. This information is needed globally, at moderate spatial resolution (hundreds of meters to a kilometer) and high frequency (daily or near-daily), and can be derived from the analysis of moderate-resolution multispectral image data obtained by operational and research satellites. The connection between the parameters most directly measured by satellites (e.g, chlorophyll concentration or a vegetation index) and those desired (e.g., primary productivity) requires significant validation effort.

(4) **How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?** It is well established that the primary cause of the stratospheric ozone depletion observed over the last two decades is an increase in the concentrations of chlorofluorocarbons (CFCs) and other halogen-containing hydrocarbons of industrial origin. The depletion has been significant, ranging from a few percent per decade at mid-latitudes to greater than

fifty percent seasonal losses at high latitudes, notably the annually recurring Antarctic ozone hole, as well as smaller, but still large, winter/spring ozone losses observed recently in the Arctic.

The abundance of chlorine in the stratosphere, the largest contributor to ozone depletion, is now reaching a peak value nearly five times greater than the natural level. This leveling off of stratospheric concentration comes several years after the peak in total chlorine abundance occurred in the Earth's troposphere. The time difference is consistent with our understanding of the delay required for transport from the Earth's surface to the stratosphere. This reversal in the evolution of chlorine demonstrates success in the implementation of the Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments. Future decrease in chlorine abundance will be quite slow, however, due to the long time scale (in excess of 100 years for some chemicals) for the removal of trace gases by natural processes. The concentrations of other ozone-depleting substances, notably bromine compounds, are not all decreasing. In fact, some observed changes are in apparent conflict with the Montreal Protocol restrictions on production.

Major scientific issues remain, related to both the susceptibility of the ozone layer to further destruction by active halogen during the next decades of peak vulnerability and the timescale for the expected recovery of stratospheric ozone during the 21st century. The scientific challenge is that ozone amount is affected by numerous other factors than chlorine and bromine, notably stratospheric aerosol loading (which can dramatically increase following volcanic eruptions), the 11-year solar activity cycle, changing concentrations of other trace gases such as methane, nitrous oxide, and water vapor. Meteorological variability is also a factor; perhaps 20-30% of the mid-latitude ozone loss may be associated with change in atmospheric dynamics, the origin and nature of which are not clear.

Accurate and consistent long-term observations of ***ozone distribution*** (both total column and vertical profiles), together with the key parameters governing its abundance, are needed to arrive at a scientifically robust diagnostic of stratospheric ozone recovery and understanding of transient variations. Very accurate absolute radiometric calibration and the maintenance of long-term instrument stability are critical requirements to document long-term variability. Although accurate knowledge of trends in tropospheric ozone is highly desirable from a scientific point of view, the limited availability of global data (especially the satellite data record) at the present time places significant constraints on its usefulness to establish such trends. As global data on the vertical distribution of tropospheric ozone become increasingly available, such trend studies may begin to be possible.

(5) **What changes are occurring in the mass of the Earth's ice cover?** The Earth's ice cover acts as an important indicator of the state of the global climate system, while at the same time exerting controls on climate that remain poorly defined. Polar ice sheets, grounded over Greenland and the Antarctic continent, constitute the largest reservoir of fresh water on the planet, corresponding to about 2% of the mass of the global oceans. Change in the mass balance of these ice sheets would result in major changes in the global volume of ocean waters and global sea-level. Airborne surveys of the Greenland ice sheet show little elevation change over most of the interior of the ice sheet above 2000 meters in height, but some areas of significant elevation change - predominantly thinning around the coast.. Assessing the rate of change of the much larger Antarctic ice sheet is a major challenge, which can only be met through repeated space-based surveys of ***ice surface topography*** at the appropriate measurement accuracy of a few centimeters. NASA is currently developing a space-based lidar altimetry system that will enable surveying of the Antarctic ice sheet to 86˚S. Smaller ice caps and glaciers, while individually minor contributors to global sea level change, have contributed collectively to perhaps one third of observed sea level rise over the last century and are important indicators of regional climate.

(6) **What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?** Changes in the Earth interior induce small, but nevertheless significant changes in the shape, rotation, and wobbling motion of the Earth. Knowledge of these relatively small changes is essential for a variety of applications (such as establishing the reference frame for precision geodesy, GPS satellite navigation, and ocean altimetry) as well as for understanding the dynamics of the Earth's interior. Monitoring the Earth's internal motions relies on a diversity of surface-based and space-based observations, particularly satellite lidar tracking, radio telescope observations, magnetic field measurements, and precision Earth gravity mapping. This information is being acquired through a worldwide cooperative effort, with a strong participation of NASA. The research strategy is a long-term cumulative effort: each new observation, obtained when a cooperative opportunity arises, adds to the precision of the reconstructed picture of the Earth's interior.

Table 4.2 Key Observations for Identifying Earth System Variations and Trends

Parameter/ Question	Implementation Details	In Situ Measurements	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Atmospheric Temperature (V1)	Passive Sounding	Radiosondes (NOAA, WWW, NASA, NDSC)	Excellent	NPOESS requirement	EUMETSAT coordination
	Active Sounding (GPS)	Global GPS network	Full demonstration needed	NPOESS requirement	EUMETSAT coordination
Atmospheric Water Vapor (V1)	Passive Sounding	Radiosondes, Ly-α, μwave (NASA, NOAA, WWW)	Satisfactory	NPOESS requirement	EUMETSAT coordination
Global Precipitation (V1)	Requires 6-8 satellite constellation for time resolution	Rain gauges, weather radar (NOAA, WWW)	Demonstrated by TRMM and passive μwave imagers	TBD; only passive μwave currently planned	Excellent – several needed
Soil Moisture (V1)	Spatial resolution and ability to penetrate vegetation required	neutron probes, lysimeters (USDA, USGS, FAO)	Very large real or synthetic antenna to be demonstrated	Highly desired; subject to operational viability	Likely with European Space Agency
Ocean Surface Topography (V2)	Prefer orbits that avoid tidal aliasing	Tide gauges (Global Geodedic Network)	Demonstrated. Development needed for denser coverage	Under study by NPOESS	Continuation of current partnerships likely
Ocean Surface Winds (V2)	Active / passive μwave technique required	ships, buoys (NOAA, WWW)	Demonstrated by NSCAT and Seawinds	NPOESS requirement may be fulfilled	Seawinds and follow-on cooperation with Japan
Sea Surface Temperature (V2)	Both IR and microwave needed for all-weather observation	ships, buoys (NOAA, WWW)	Excellent	NPOESS requirement	EUMETSAT coordination
Sea Ice Extent (V2)	Microwave sensors needed for all-weather measurements	Ships, airborne reconnaissance (Navy, USCG, NOAA)	Excellent	NPOESS requirement	NASDA cooperation
Terrestrial Primary Productivity (V3)	1 km or better resolution global coverage required	Crop, forest inven. (USDA, FAO, NSF, GTOS)	Excellent	NPOESS requirement	EUMETSAT coordination
Marine Primary Productivity (V3)	Very precise inter-satellite calibration is essential	NASA-SIMBIOS time series studies	Demonstrated	Partially provided by NPOESS	Cooperation with Japan, Europe possible
Total Column Ozone (V4)	Long-term high accuracy needed for trend studies	Dobson, Brewer, FTIR, UV/VIS (NASA, NOAA)	Excellent	NPOESS requirement	EUMETSAT coordination
Ozone Vertical Profile (V4)	Good vertical resolution needed near tropopause	Ozonesondes, lidar, μwave , IR, (NASA, NOAA)	Excellent	NPOESS requirement	International coordination
Ice Surface Topography (V5)	Excellent vertical resolution and accuracy needed for mass balance studies	GPS (NASA, NSF)	ICEsat lidar altimetry demonstration	Not currently an operational requirement	Coordination with European radar altimetry satellite
Gravity Field (V6)	Requires high precision	Geodetic networks	GRACE demo. pending	DOD interest in precise geoid	Possible
Terrestrial Reference Frame (V6)	Derived mainly from ground observation and precision satellite tracking	SLR and GPS networks	Excellent	Multi-agency infrastructure	Multi-national ground network
Motions of the Earth's Interior	Inferred from mult. measurements --	SLR, GPS, VLBI networks,	Excellent	Multi-agency infrastructure	Excellent for exploratory

(V6)	space/ground based	magnetometer obs.			mission(s)

4.2 Primary Forcings of the Earth System

Observed variations and trends in the Earth system are the combined result of natural variability and forced changes. In order to identify the origin of these changes, a necessary condition is to quantify the primary forcings induced by the Sun or human activities on the Earth system. Two kinds of human actions have passed the threshold of global significance, changes in the composition of the atmosphere and changes in land cover and land use. Variations in the radiation output of the Sun, and internally generated changes in the Earth's topographic surface are superimposed on these anthropogenic forcings. Systematic and accurate measurements of all forcing factors are indispensable if one is to attribute the observed changes in the global environment to specific causes. The key observational parameters required for characterizing forcings of the Earth system are summarized in Table 4.3.

(1) **What trends in atmospheric constituents and solar radiation are driving global climate?** The primary external forcing affecting the Earth is change in the Sun's total energy output. Variations in total solar radiation per unit of Earth's surface (***total solar irradiance***) are currently quite small (less than 0.2% over an 11 year solar cycle, with relatively small day-to-day variations associated with sunspots, etc.), but total solar irradiance may have been substantially lower during the recent solar activity minimum which coincided with the general cooling of climate in the 17^{th} century. Changes in solar output could have important consequences for the Earth's climate, so maintaining an accurate record of total solar irradiance is a necessary foundation for Earth system science. Given the small temporal variations and the difficulty in assuring accurate in-space calibration of these measurements, overlap between successive instruments is a fundamental requirement.

The Sun's energy output is considerably more variable in the ultraviolet part of the spectrum. The shorter the wavelength, the larger the variability – ranging from some 5% over a solar cycle at the wavelengths involved in stratospheric ozone production, to a factor 2 in the hydrogen Lyman alpha region of the spectrum that affects the mesosphere and thermosphere. Assessments of the evolution of ozone variations and upper atmosphere temperatures must account for the solar cycle induced variation in their distribution. The extent to which the resulting larger chemical and thermal variations in the stratosphere and above can be propagated downwards and then influence climate in the lower atmosphere is a current research problem. Continued long-term monitoring of spectrally resolved ***solar UV irradiance*** is therefore required to address issues of ozone and climate.

Stratospheric aerosols that result from large volcanic eruptions can significantly cool the Earth's surface, as has been demonstrated by several volcanic eruptions (most recently, that of Mt. Pinatubo in 1991). A large volcanic eruption can raise the stratospheric aerosol loading by a factor of 100 globally, and decay towards background levels is slow (several years). Background aerosol levels may also be raised by aviation and other industrial activities; continued observations of stratospheric aerosol amount are needed to characterize both the long-term and shorter-term variability. Tropospheric aerosols, on the other hand, can either cool or warm the atmosphere depending on their properties. The spatial and temporal variation of troposopheric aerosols is sufficiently large that frequent global space-based observations are needed if their presence is to be adequately characterized. Global observations of ***total aerosol amount*** and stratospheric ***aerosol vertical profiles*** are required to monitor this important climate forcing globally. Obtaining complete information on aerosol properties, including sufficient information on optical, radiative, and chemical properties that can be used in models remains a research challenge, however, requiring a combination of advancedspace-based measurements together with *in situ* airborne and ground-based remote sensing observations.

Long-lived trace gases such as carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons are all important for trapping infrared radiation in the atmosphere and contributing to global warming.

The major observational requirement for most of these is to monitor their total concentrations is *in situ* measurements of surface level concentrations of these trace gases. Ozone is another radiatively important trace gas in the troposphere, and has sufficient spatial and temporal variation that its concentration must be known throughout the troposphere. On the other hand, estimating the sources and sinks of these trace constituents at the surface of the Earth requires frequent and dense observations of spatial and temporal variations in their concentrations, as well as knowledge of the natural, agricultural, and industrial processes that are most directly responsible. The first measurements of the distribution of total methane are only now becoming available. Corresponding measurements for carbon dioxide, of enormous scientific interest for improving our knowledge of the carbon cycle, will require the development of new measuring technologies. Models will play a critical role in converting observations into the source-sink information that is desired.

(2) **What changes are occurring in global land cover and land use, and what are their causes?** Biophysical phenomena and human activities that drive changes in land cover and land use include changes in agricultural practices, natural and human-triggered fires, drought and flooding, forest exploitation and clearing, grazing by domestic animals, and urbanization. Each of these phenomena can cause considerable disturbance or stress in natural and managed ecosystems, and consequently the whole Earth system. In combination, these changes in land cover and land use have grown to become a major factor of landscape modification, affecting ecosystem productivity and biogeochemical cycles; regional climates and hydrologic regimes; and soil erosion and sediment transport. Land use management practices, in particular, can create “sharp boundaries” that might not exist in nature, and the environmental effects of these will need to be understood. Documenting these changes and investigating their causes requires observations at the spatial scales of the disturbance or stress factors themselves, often on the order of tens of meters. Understanding the origin of the changes may require consideration of detailed socio-political factors operating in a given region. The observational requirements are for periodic global inventories of ***land cover and land use***, derived from observations repeated once or a few times per year. This information is obtained from systematic global multispectral mapping of the land cover at spatial resolution of a few meters. The potential of meter-class resolution ("hyperspatial") mapping is being investigated for sharper diagnosis of causal factors and likely future trends.

(3) **How is the Earth’s surface being transformed and how can such information be used to predict future changes?** The current knowledge of the dynamics of the Earth's interior is far from being advanced enough to enable specific and accurate prediction of hazardous geological events, such as earthquakes and volcanic eruptions. The scientific objective, at this time, is to acquire a fundamental understanding of the landscape-forming processes which explain the history and evolution of geologic systems, in order to lay the basis for assessment of potential natural hazards. Recent advances in land surface geodesy allow measuring the deformation of the Earth crust over time periods much shorter than earthquake or volcanic eruption cycles. In order to arrive at useful assessments of geological risks, it would be necessary to characterize these ***deformation and stress accumulation*** phenomena over a complete cycle (e. g. before, during and after seismic events). This cannot be done directly, but the information can nevertheless be assembled by combining observations from a number of sites at different stages in their own cycle. The main sources of information are, at the local scale, dense arrays of precision GPS receivers anchored in the ground and, at the regional scale, the "interferometric" analysis of synthetic aperture radar (SAR) image data.

Table 4.3 Key Observational Requirements for Determining Primary Forcings on the Earth System

Parameter / Question	Implementation Details	In Situ Measurements	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Total Solar Irradiance (F1)	High absolute accuracy, overlap of successive records required	global surface networks (BSRN, WRDC, SURFRAD)	Excellent	NPOESS requirement	Possible
Solar UV Irradiance (F1)	Spectral resolution & good radiometric accuracy req'd	USGCRP UV network, NDSC (multiagency)	Excellent	NPOESS measurement planned	Strong history of cooperation
Stratospheric Aerosol Distribution (F1)	Good vertical resolution and large dynamic range required	Lidar, backscatter-sondes (NASA, NOAA, NSF)	Excellent	NPOESS meas. possible but resolution is problematic	Possible
Total Aerosol Amount (F1)	Global coverage over ocean and land needed	AERONET, USDA network, NOAA/BSRN, DOE/ARM	Excellent	NPOESS requirement	Possible
Aerosol Properties (F1)	Need in situ and ground-based measurements	AERONET, NOAA/CMDL, airborne aerosol spectrometers	Further development needed for space measurement	Not currently an operational requirement	Possible, important for ground-based measurements
Surface Trace Gas Concentration (F1)	Ground-based measurements fulfil requirements	NASA AGAGE, NOAA flask network and CO_2 meas.	Need simpler instruments with better time resolution	NOAA flask sampling network, NASA AGAGE	Helps support ground network
Volcanic Gas & Ash Emissions (F1)	Global observation of ash and gas plumes	In situ optical calibration	Further progress needed to characterize tropospheric constituents	Significant on account of impact on aviation	Possible
Fire Occurrences (F2)	Global observation of infrared and vis/near-ir; hyperspectral for fuel load	Aeronet (NASA), burn scar inven. (USFS, int'l.), In situ optical calib.	Excellent	NPOESS EDR application	NPOESS EDR application
Trace Gas Sources (F2)	CO_2 column mapping is greatest priority	Flask network (NOAA), Ameriflux (DOE, USDA, NASA), FluxNet	Technical developments needed for exploratory mission	Not currently an operational requirement	Possible
Land Cover/ Land Use Inventories (F2)	High spatial resolution required (few tens of meters)	Land Cover Maps (USGS), Veg. Inventories (DOI, USDA)	Excellent, need to reduce cost	Not currently; working with USGS	Commercial data purchase likely
Surface Stress and Deformation (F2)	Special focus on active earthquake and volcanic regions	Regional GPS networks, geological obs.	Excellent	Joint support of ground arrays by local agencies	multi-national support for ground arrays

4.3 Earth System Responses and Feedback Processes

Two scientific strategies are conceivable to study the responses of the Earth system to natural and human-induced forcings. The first is the holistic approach, based on analyzing observed changes in the Earth system taken as a whole. The second is the analytical approach, based on detailed characterization of elementary processes involved in the response mechanism, and simulation of the interplay among these processes with mathematical models. Both methods actually aim at the same objective, that of identifying the signatures of individual forcing factors and modes of natural variability in the response of the Earth system. The first approach relies on the same systematic measurements and observational records as required to document natural variability and trends (see 4.1 above). The second approach requires specific new observations that enable in-depth studies of the operative processes. As elementary processes usually involve shorter time-scales than the Earth system itself, intensive but time-limited studies (e. g. dedicated one-time exploratory missions and process-oriented ground-based and airborne field studies) can provide sufficient information to reach conclusive results. Based on the criteria laid out above, scientific priority is given to "feedback processes" that have the largest potential for amplifying or damping changes in the global Earth system (and may thus induce large uncertainties in potential responses). The observational paramters most closely associated with response studies are summarized in Table 4.4.

(1) **What are the effects of clouds and surface hydrologic processes on climate change?** The formation, life cycle and optical properties of cloud systems remains, to this day, the largest source of uncertainty in simulations or predictions of global climate change. Clouds affect climate both directly, through their controlling effect on the planetary radiation balance, and indirectly, through vertical transport and condensation of water vapor that controls upper-tropospheric moisture and its greenhouse effect. Conversely the formation, life cycle and radiative properties of clouds are governed by the relative humidity of surrounding clear air. Thus, the feedback effects involving climate, clouds, and surface water can be significant and must be understood.

Cloud processes involve complex 3-dimensional interactions between fluid dynamical motions, microphysical and optical properties of liquid and ice cloud particles, pre-existing condensation nuclei (aerosols), and the dynamics of the mesoscale weather systems in which they are embedded. These complex interactions generate extremely diverse cloud systems and cloud types, each involving different controlling microphysical and meteorological factors. Understanding these complex phenomena requires observations that simultaneously (1) resolve the 3-dimensional structure of cloud systems, (2) cover a representative sample of all different cloud types and distributions of condensation nuclei and aerosol particles that affect cloud particle distributions, (3) characterize the large-scale weather patterns and/or mesoscale disturbances that generate the clouds, and (4) relate cloud dynamics and optical properties to large-scale climate variables, especially the thermodynamic structure of the troposphere and radiation fluxes at the top of the atmosphere. These observational requirements have only been partially met so far by regional field observation campaigns focused on one or a few cloud types.

The ***surface hydrologic processes*** that govern continental water budgets and the availability of fresh water resources also are the result of complex physical and biological processes taking place at the land surface. Land surface hydrologic processes control river flow and available water resources, diurnal variations in surface temperature, and the availability of soil moisture that sustains the growth of terrestrial ecosystems. So far, basic hydrologic processes have been examined mainly at the scale of relatively small river basins or catchments. Quantitative understanding of hydrologic processes over large areas, commensurate with the scale of climate phenomena, will require a breakthrough in large-scale observation of hydrologic properties and physical climate drivers. Specific observational requirements to address this problem include (in addition to atmospheric properties, precipitation and surface radiation fluxes) exploratory measurements of soil moisture, snow accumulation and snowpack, and the transition between frozen and thawed soil conditions.

(2) **How do ecosystems respond to and affect global environmental change and the carbon cycle?** Terrestrial and marine ecosystems are affected by multiple environmental stresses and disturbances, as well as natural cycles, that can result in changes in primary productivity, continental and oceanic carbon sources and sinks, the biogeochemical cycles of carbon and important nutrients, surface energy balance, and surface hydrological processes. Response processes in ecosystems need to be understood at the level of basic functional and structural changes. Ecosystem functional responses involve changes in physiology and biogeochemical cycling. Ecosystem structural responses involve changes in species composition, biomass density, canopy architecture, and distribution patterns across a landscape or within the ocean. Ecosystem responses, in turn, can provide feedback to the climate system and atmospheric chemistry through alterations in the fluxes of water, energy, and trace gases to the atmosphere.

In order to estimate carbon dioxide sources and sinks on the land, ecosystem science needs to quantify the responses of terrestrial ecosystems to disturbance in terms of ***biomass changes***, and consequent carbon sequestration or emission. There is no direct method for estimating total biomass by remote measurements, but quantifying above-ground biomass appears feasible, based on experiments performed from the Space Shuttle. A fuller implementation of this concept is under development, and future exploratory projects have been proposed, to address biomass accumulation in ecosystems responding to disturbance.

The global ocean carbon cycle is dominated by the solubility pump (changes in the ability of the ocean take up CO_2), which is driven by changes in ocean temperature and circulation. The biological pump is another critical component of the ocean carbon cycle and involves sinking, diffusion, and active transport of biologically-produced carbon compounds. The CO_2 balance of the atmosphere and ocean can be affected by the biological pump through the effects of changes in limiting nutrient supplies. The observational requirements are long-term observations of the ocean circulation and temperature, ocean productivity, and estimates of the major phytoplankton groups in the upper ocean. Coastal ecosystems are highly productive and extremely variable, and human impacts on the ocean are greatest in coastal regions, as are the impacts of climate variability and sea-level rise. Thus, priority is given to quantifying variability in ***coastal primary productivity***. Coastal biological processes are constrained by geography and can be characterized by observations that resolve weather-induced changes (e. g. transient sediment transport events) and tidal fluxes. The principal observational requirement is quasi-continuous observation of ocean color in selected coastal regions, with appropriate spatial, temporal and spectral resolution.

Quantifying regional ***carbon sources and sinks*** for both the ocean and land can be approached through the inversion of precise measurements of spatial and temporal variations in the total column amount of CO_2 in the atmosphere. The method, founded on the use of inverse atmospheric transport models for analyzing atmospheric concentration data, has the potential for independent direct determination of global CO_2 fluxes. Possible space-based measurement methods are at an early conceptual stage. Information on vertical variations in atmospheric CO_2 may be needed as well to help understand the column measurements. The extent to which such measurements are needed is a research question, however.

(3) **How can climate variations induce changes in the global ocean circulation?** In addition to the main currents and vortices visible at the surface, the ocean also sustains a slow but massive overturning circulation, which involves the formation of "deep water" that sinks to intermediate or bottom depths, and a general upwelling motion that maintains the sharp separation of superficial waters from the deep ocean. This overturning circulation has profound implications on the long-term storage of excess heat and chemicals in the ocean's depths; the recycling of nutrients; marine productivity and the carbon cycle; and the long-distance transport of heat from one ocean basin to the

other. A potential transition from the current circulation regime of the Atlantic ocean to a regime where deep water formation is blocked would have a major climatic impact on the North Atlantic region. There is strong paleoclimatic evidence that such transitions did occur in the past, notably during the recovery from the last glacial episode.

Deep water formation is quite sensitive to a freshening of surface waters, either through the import and subsequent melting of sea ice, or climate-induced changes in the fresh water balance of the ocean at tropical and mid-latitudes. Since atmospheric temperature at high latitude always falls below the freezing temperature of sea water, the fate of superficial waters and their ability to sink into the deep ocean depends upon their pre-existing salinity (salinity and temperature are the two parameters that determine water density). Thus, the principal observational requirements for investigating the potential for a transition in ocean circulation regime are (exploratory) measurements of ***sea surface salinity*** and ***sea-ice*** (formation and life cycle)**.**

(4) **How do stratospheric trace constituents respond to climate change and chemical agents?** Climate change associated with increasing concentrations of trace gases will affect the distribution of ozone in the stratosphere, and vice versa. The connection between atmospheric temperatures and stratospheric composition is equally well established. A striking example is the enormous interannual variations in wintertime ozone concentration over the Arctic, highly correlated with changes in stratospheric circulation and temperature driven by the troposphere. Long, cold winters, such as occurred in 1996-1997, enhance ozone destruction and make Arctic conditions more similar to those in the Antarctic that enable the annual springtime depletion of ozone.

It has been suggested that climate change will affect the way in which the troposphere influences the stratosphere, and would thus indirectly affect stratospheric ozone. The impact would be particularly strong if the wintertime polar vortex became more stable. Similarly, chemical reactions that occur on the surface of stratospheric aerosol and/or cloud particles are temperature dependent; even a small decrease in temperature could cause a significant increase in the rates of these reactions. Changes in stratospheric water vapor, associated with changes in fluxes through the tropopause, could also enhance the formation of aerosol and cloud particles that facilitate ozone destruction. Furthermore, since ozone absorption of solar UV radiation causes stratospheric heating, a decrease in ozone amount would result in further cooling, and further accelerate ozone losses. There is already strong evidence of cooling in the lower stratosphere, which constitutes one of the largest temperature signals measured in the atmosphere over the past 20 years.

Improving our understanding of this highly interactive system calls for detailed investigation of the relationship between the distributions of ozone, water vapor, aerosols, temperature, and relevant trace constituents, notably chlorine and bromine compounds and nitrogen oxides. In view of the high spatial variability of these phenomena, good horizontal and vertical resolution will be needed, especially in the vicinity of the tropopause (upper troposphere and lower stratosphere).

(5) **How is global sea level affected by climate change?** There are two major processes by which global climate change may lead to a rise in sea level. First, thermal expansion of liquid water may raise sea surface levels to the extent that the oceans continue to warm in the future. Second, melting of the polar ice sheets has the potential to lead to an increase in the volume of liquid water on Earth. In order to understand the possible impact of the latter process, the way in which ice sheets respond to changes in climate must be understood, which requires more detailed knowledge of the internal workings of polar ice sheets.

The traditional concept of continental ice sheets as a sluggish component of the Earth system, changing with literally "glacial" slowness, is being superseded by the realization that parts of the ice mass are actually capable of changing substantially over periods of a few years or decades. The dramatic calving of vast tabular icebergs from relatively unstable ice shelves surrounding the Antarctic Peninsula is a portent of such changes. The first high-resolution radar survey of the Antarctic ice sheet discovered massive ice-streams, huge rivers of ice reaching far inland and leading to the ice sheet margin. Assessing the potential for relatively fast ice flows that could discharge vast volumes of ice in a matter of decades instead of centuries is an important problem, considering the potential impacts of an accelerated rate of sea level rise. The observational requirement is mapping the ***velocity fields*** of the two great ice sheets of Greenland and Antarctica in order to identify their dynamic regions and estimate the mass fluxes of major ice streams. The relevant (synthetic-aperture radar) data might be obtained commercially, or from dedicated national or international scientific measurement missions.

(6) **What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?** The continued growth of the world's population and increasing industrial development imply increasing human impacts on the global atmosphere. As fossil fuel combustion increases, emissions of trace gases other than carbon dioxide will also rise, notably nitrogen oxides, carbon monoxide, hydrocarbons, and other precursors of ozone production, as well as aerosol particles and their precursors.

Satellite observations provide evidence of the large-scale effects of such emissions on the troposphere. The highest tropospheric ozone concentrations observed in this way were found in summertime over mid-latitude regions of the northern hemisphere, and also over the tropics in regions affected by biomass burning. Aircraft observations have demonstrated that plumes of pollution produced by fires can be transported thousands of kilometers to otherwise pristine regions of the atmosphere (e. g., over the Pacific Ocean). Surface level trace gas measurements made on the west coast of the United States show enhanced levels of ozone precursors during periods of rapid and direct transport of air from East Asia.

There are currently few global observations of tropospheric ozone, key trace gases or aerosol particles, and none providing nearly the required vertical resolution. Global measurements of key tropospheric constituents at high vertical and temporal resolution are the condition for progress in understanding the large-scale transport, physical removal and chemical transformation of chemical effluents in the troposphere. In the interim period, some of the high vertical resolution measurements needed can be obtained from balloon and airborne observations (albeit with very limited spatial and/or temporal coverage), as well as the lower resolution space-based measurements that are becoming available for the first time. The capability to observe, from geostationary or Lagrange point platforms, the diurnal evolution of ozone and/or aerosol amounts in polluted regions may also provide significant insight into the balance between processes which result in chemical transformation, physical removal, and physical transport of pollutants.

Table 4.4 Special Observational Requirements for Response and Feedback Process Studies

Parameter / Question	Implementation Detail	In Situ Measurements	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Cloud System Structure (R1)	Multispectral visible and IR radiometry	Radiosondes, lidar (NASA, NOAA, FAA)	Excellent	NOAA & NPOESS requirement	EUMETSAT and Japan's ADEOS/GLI
Cloud Particle Properties and Distribution (R1)	Active sensor to resolve three-dimensional structure	none	Demonstration of cloud radar and lidar pending	Not currently an operational requirement	Domestic and international
Earth radiation Budget (R1)	Broadband radiometry	none	Excellent	Planned on NPOESS	Possible
Soil Moisture (R1)	Spatial resolution and ability to penetrate vegetation required	neutron probes, lysimeters (USDA, USGS, FAO)	Approaching readiness (done from aircraft)	Highly desired; subject to operational viability	Likely with European Space Agency
Snow Cover & Accumulation (R1)	Need to assess snow depth or water equivalent quantitatively	Snow transects (NOAA/NWS)	Awaiting demonstration	NPOESS requirement for snow cover	Possible
Freeze-Thaw Transition (R1)	Need to assess in all sky and surface conditions	Not a routine measurement	Awaiting demonstration	Desired	Possible
Biomass (R2)	Based on resolving canopy vertical structure; requires active lidar sensor	Crop/Timber yield (USDA, DOI), carbon database (DOE)	Demonstration pending (VCL)	Not currently an operational requirement	Possible
Marine Productivity in Coastal regions (R2)	High spatial and temporal resolutions needed	NASA-SIMBIOS; Coastal bio-optics (NOAA, EPA)	Excellent	Possible NPOESS derived product	Active currently
Carbon Sources and Sinks (R2)	CO_2, CH_4 column mapping is most promising approach;	Flask network (NOAA), Ameriflux/Flux Net (DOE, USDA, NASA)	Experimental technique, needs further develop.	Not currently an operational requirement	Possible
Sea Surface Salinity (R3)	Very high radiometric precision needed for passive µwave observation	Ships and moored/drifting buoys (NOAA/NSF)	Approaching readiness (done from aircraft)	Unfulfilled NPOESS requirement	Likely with European Space Agency
Sea Ice Thickness (R3)	Significance of ice freeboard observations remains to be established	Moored buoys (ONR)	High spatial resolution radar; develop. needed	Desirable	Possible with domestic / international partners
Atmospheric Properties in Tropopause Region (R4)	Need ozone, water vapor, temperature at high vertical resolution	Sondes (WWW, NOAA)	Limb viewing sensors not yet demonstrated	Not currently an operational requirement	Interest exists
Polar ice sheet velocity (R5)	Synthetic aperture radar interferometry; high latitude coverage (polar orbit) needed	GPS (NASA, NSF)	Demonstrated	Desireable	Possible
Tropospheric Ozone and Precursors (R6)	Need excellent vertical resolution through entire troposphere, implies active lidar sensor	Airborne in situ for DC-8, R-2, WB-57	Experimental technique, needs further develop.	Not currently an operational requirement	Interest exists

4.4 Consequences of Global Changes

The consequences for human civilization are the root of societal interest in the prospects for global environmental change. Changes in the Earth's land cover and land use are pervasive and increasingly rapid; few landscapes are unaffected and the coastal ocean is increasingly disturbed. Changes in global mean climate quantities (e. g. surface temperature) elicit broad interest because of the surmise that relatively small variations in atmospheric composition and greenhouse effect, atmospheric circulation and ocean temperature, land cover or land use, could results in serious disruptions of the natural environment. Concern about human consequences is not limited to considerations of the future. Currently occurring changes can affect properties of direct interest to human societies: the availability and quality of water, the quality of air, the health and diversity of ecosystems, the ability for diseases to spread, and the sustainability of agricultural production.

Consequences can take many forms, from impacts on air quality to changes in solar UV radiation, loss of biodiversity, or degradation of ecosystem productivity. These impacts are of considerable societal significance and warrant dedicated local investigations that are beyond the scope of the NASA Earth science research program. Assessing the existing or potential impacts of environmental change is a widely shared responsibility of several partner agencies of the USGCRP; the ESE's participation to this effort involves, in particular, the deployment of unique remote sensing assets and is handled principally through the ACE program. Three research areas involving large-scale or even global impacts are given particular attention in the ESE research program.

The observational parameters most relevant for consequence studies are summarized in Table 4.5.

(1) **How are variations in local weather, precipitation and water resources related to global climate variation?** The striking manifestations of "El Niño weather" in many regions of the world, including western and southeastern US, are a clear example of the climate-weather connection. Much remains to be learned, however, about the relationship between observed trends or anomalies in global-mean atmospheric state and associated changes in the path, frequency and intensity of weather systems. The information needed to document changes in the global atmospheric circulation and climate was considered in 4.1(1) and 4.3(1) above. The new challenge is that of relating the large-scale atmospheric circulation to the life cycle of mesoscale storms (e. g. hurricanes) and other severe weather systems (e. g. tornado-generating rainstorms), and then understanding how that relationship might change in a future climate. Another challenge is that of deriving quantitative precipitation predictions from weather forecasting models. Both topics are actually central objectives of the US Weather Research Program. The special observation requirements to address these objectives are principally ***global precipitation*** and ***ocean surface wind***, the latter providing a direct measure of storm tracks, strength, and life cycle over the expanses of the ocean. Another potential source of observational data on the life cycle of mesoscale storms (principally over land) is the measurement of the 3-dimensional structure of atmospheric ***temperature, moisture and wind*** around storm cells. Other developmental observations (e. g., imaging lightning strokes from a geostationary platform) may also reveal important new information regarding thunderstorms, severe weather and rainfall.

The other major impacts of global climate change are regional hydrologic anomalies, floods and droughts, as well as long-term variations in the availability of water resources, changes in the distribution and/or seasonal variation of wetland area, and the volume of inland water bodies (e.g. the Caspian sea). The principal challenge in this domain is also the quantitative prediction of precipitation. In addition, exploratory observations of soil moisture, snow accumulation, and freeze/thaw transitions (see the first question in the repsonse section) will provide critical process-level information needed for predicting the hydrologic consequences of regional climate anomalies. Basic hydrologic data such as ***river stage height*** and/or ***discharge rate*** are often unavailable for scientific studies, even for some of the world largest river basins. As the competition for water resources increases, it is even less likely that such basic hydrologic data will be freely exchanged in the future. This information is an essential observational requirement for the study of regional hydrologic impacts. For measurements of these quantities, use of in situ measurements to help relate measurements of stage height to discharge rate are of particular importance.

(2) What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity? To understand the consequences of land cover and land use change for sustainability of ecological goods and services, both the biophysical and the human factors that both drive and constrain land cover and land use changes must be addressed. Natural and human-induced disturbances such as fire, insect infestations, and logging may change large areas of the Earth's surface, but more subtle changes that result in habitat degradation and fragmentation (e. g., forest clearing and/or burning, land use change associated with urbanization) or the introduction of non-native species can lead to diminished ecosystem functionality, redistribution of species within an area, and/or loss of biodiversity. The impacts on agriculture, forestry, and water resources; biodiversity; carbon storage or release; and the geographic distribution and activities of human populations need to be quantified. Satellite observations, especially high-resolution multispectral image data acquired to estimate primary productivity, document land cover patterns, or assess change in ecosystem properties (see 4.2), also can contribute to assessing such consequences and identifying those regions most susceptible to changes in species distributions. The verification of these changes and the identification of the impacted species is best carried out through *in situ* studies that will typically be carried out by agencies other than NASA.

(3) **What are the consequences of climate and sea level changes and increased human activities on coastal regions?** Coastal regions, including beaches, low lying lands near oceans, estuaries, and river deltas, are of particular importance to human societies, especially since the population that lives close to the ocean is fast increasing worldwide. Such regions are highly susceptible to the effects of sea level rise (including wetlands loss), disturbance by human activities, and land cover changes in adjacent watersheds, as well as a potential increase in the frequency and amplitude of storm surges associated with the landfall of large storms. Surface erosion due to wind and wave conditions, wind damage, flooding, sediment deposition and chemical pollution (both direct and through runoff from agricultural and urban regions), and hazardous biological phenomena (e. g. algal blooms) are the principal stresses and disturbances observed in coastal regions. Conversely, coastal wetlands in the tropics appear to be large natural sources of ozone-destroying halogenated chemicals. The challenge is characterizing these changes over a long enough period to understand how coastal regions respond to simultaneous changes to these multiple stress factors, and how the forcing factors and repsonse mechanisms might change in a changing climate.The principal observational requirement, in addition to meteorological information and sea-level data, is for repeated multispectral observation (which can provide information on the distribution and properties of biological material) of coastal regions at the highest practicable spatial and temporal resolution.

Table 4.5 Special Observational Requirements for Studying the Consequences of Global Change

Parameter / Question	Implementation Details	In Situ Measurements	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Global Precipitation (C1)	Requires 6-8 satellite constellation for good time resolution	raingauges, weather radar (NOAA, WWW)	Demonstrated via TRMM and passive μwave imagers	Yes; only passive μwave currently planned	Excellent – several needed
Ocean Surface Winds (C1)	Active μwave technique	ships, buoys (NOAA, WWW)	Demonstrated by NSCAT and SeaWinds	Yes	Seawinds cooperation with Japan; EUMETSAT
	Passive μwave radiometry / polarimetry to be demonstrated	N/A	Windsat/Coriolis demonstration funded by DOD, USN, NPOESS	NPOESS requirement may be fulfilled	Possible
Meteorological Properties Around Storms (C1)	Requires vertical profiling from a geostationary platform	Radiosondes (NOAA, WWW)	Demonstration planned with GIFTS	Yes	Possible
Lightning Rate (C1)	Requires geostationary implementation for temporal resolution	Sferics (NOAA)	Demonstrated by OTD and LIS	Yes	Possible
River Stage Height/ Discharge Rate (C1)	Requires high precision, vertical resolution, and frequent sampling	River gauges (USGS)	Capability demonstrated by Topex/Poseidon	Not currently an operational requirement	Not known
Primary Productivity (C2)	Global 1 km or better resolution needed	NASA-SIMBIOS, GOOS, GTOS, crop, forest inventories (USDA, FAO), LTER (NSF)	Excellent	NPOESS requirement	EUMETSAT coordination
Land Cover / Land Use Change (C2)	High spatial resolution required	Land cover maps (USGS), veg. Inventories (DOI, USDA)	Excellent, need to reduce cost	Not currently	Commercial data sets
Coastal Region Properties and Productivity (C3)	Multispectral radiometry at high spatial and temporal resolution from GEO	Coastal observations (NOAA, EPA)	Excellent	Not currently	Possible

4.5 Global Change Prediction or Assessments

How well can we predict the changes to the Earth system that will take place in the future? Beyond the broadly shared interest in understanding the causes (why?) and the mechanisms (how?) of environmental changes, the capability to deliver specific and verifiable predictions of future environmental events or trends would be of considerably higher practical value. In particular, it is important that individual, governmental, or business decisions which depend on consideration of the future environment be made on the basis of the best possible scientific information. Such decisions can have important consequences at all levels of society. When future forcings are uncertain, multiple forecasts must be carried out in order to define the probable range of responses.

Most environmental change issues of importance to decision makers are of local or regional scope, rather than global. While the focus of the ESE research program is on scientific questions concerning the global environment and large-scale Earth system phenomena, it is often the case that knowledge acquired about global changes and trends can be translated into regionally specific but only statistically valid predictions or assessments. Providing prediction services is the mission of responsible operational agencies, not NASA. On the other hand, it is incumbent upon NASA, like other research and development agencies, to assist in the improvement of such prediction services of great societal importance, within the scope of its special capabilities. These capabilities include various global observing assets and predictive models, as well as the capability to combine observations and models. It is apparent that successful prediction is the ultimate step in the progression from basic global observations of Earth system variations and trends (both national and human-induced), to understanding the internal processes and responses, to assessing the consequences. The ESE research program is especially relevant to five types of prediction or assessment of future changes.

The new observational parameters most clearly associated with improved capability for prediction are summarized in Table 4.6. Although all the variables cited in the previous tables may be thought of as potentially contributing to this improvement, this table lists only those parameters that are considered to have the greatest potential impact on prediction, focusing on the short-term.

(1) **How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?** Accurate forecasting of weather is of considerable significance for the protection of lives and property. Improving the accuracy of short-term predictions and increasing the period of validity of long-range forecasts has great practical interest and is a great scientific challenge. While weather prediction is the primary responsibility of operational agencies, such as NOAA in the US, scientific advances made in developing more accurate climate and/or Earth system models, as well as more effective methods for ingesting new types of observations, are directly applicable to the improvement of operational forecasting systems. Experience showed that synergy between operational weather forecasting practice and the development of new observation systems or products is an effective engine of progress in both domains. The principal thrusts of ESE's cooperation with operational weather services are (1) participation in the development of precursor operational instruments for application to various operational environmental satellite systems, (2) development of new data products originating from space-based observing systems, and (3) collaboration in the development and experimentation of improved atmospheric circulation models and data assimilation schemes.

The ESE participates in the development and flight demonstration of future operational NPOESS and GOES instruments, and the development of innovative remote sensing systems that may find operational applications in the future (e. g. tropospheric wind sounder). The ESE also supports cooperative modeling research and development efforts with NOAA's National Centers for Environmental Prediction, as well as the National Center for Atmospheric Research.

(2) **How well can transient climate variations be understood and predicted?** Short-range climate forecasts (for periods from a season to a year) are of considerable value to businesses, resource management agencies, and farmers. Improved atmospheric circulation models and coupled ocean-atmosphere models have demonstrated predictability in climate variations up to several months in advance for some regions of the world. Numerical simulations have also demonstrated the sensitivity of such predictions to a number of land surface and ocean circulation parameters. An essential condition for capitalizing on these scientific advances is access to the relevant geophysical information and the ability to ingest this information through more effective data assimilation methods. The information most useful for this application includes, in order of increasing persistence or "memory": ***ocean surface winds***; ***continental soil moisture***; ***sea surface temperature***; ***ocean sub-surface temperature and currents*** (alternatively, ***ocean surface topography***). Initial values of tropical ocean parameters are principally useful for ENSO prediction, while continent-scale soil moisture data (not yet available with the required coverage and accuracy) significantly influence numerical predictions of summertime precipitation over the interior of continents. Recent progress in seasonal prediction has come from realistic representation of mesoscale weather systems in coupled global atmosphere-ocean models (to be expected since the principal manifestations of transient climate anomalies are changes in storm track, frequency, and strength). The ESE's research program contributes to progress in all aspects of this problem, from improvements of models and data assimilation methods to advances in global observation.

(3) **How well can long-term climatic trends be assessed or predicted?** The long-term prediction of potential changes in global climate is the most daunting challenge of all, because such predictions depend critically on accurate representation of all relevant "feedback processes" in the atmosphere, ocean, soil and ice, and the biosphere, as well as realistic scenarios about future changes in primary forcing factors. Among the most critical problems are understanding the atmospheric processes that vertically redistribute energy, water and other constituents in the atmosphere; the relationship between cloud radiative properties and the underlying meteorological conditions; the partitioning of rain and snow among evaporation, storage and runoff; the effects of changes in land surface and land use on the latter; the exchanges of energy, fresh water, and trace constituents between the atmosphere and the ocean; the formation and evolution of sea ice; the influence of physical climate on biogeochemical cycles; and the trace gas composition of the atmosphere and response to changes atmospheric circulation. Building confidence in such predictions requires success in all four preceding steps in the science strategy.

Another piece of information that will eventually be needed for specific predictions of multi-decadal climate changes is an accurate description of the state of the deep ocean circulation globally, a task already undertaken under the international World Ocean Circulation Experiment and follow-on global ocean observing and data assimilation programs. Because of the fundamentally chaotic nature of fluid and climate system dynamics, any long-term prediction effort should be based on not just one, but a number of alternative model runs in order to quantify and minimize the range of natural variability. Such "ensemble forecasts" pose major computational demands that cannot be fulfilled without significant increase in computing capabilities and developments in computational software and algorithms used in climate models.

(4) **How well can future atmospheric chemical impacts on ozone and climate be assessed?** Prediction of the evolution of atmospheric trace constituent composition is intimately linked to that of the meteorological conditions under which chemical and transport processes occur. The chemical

constituent of greatest interest is ozone, which both protects the Earth from biologically damaging solar ultraviolet radiation, and is an active chemical agent pollutant that affects both plant and animal life. Ozone responds (for both production and destruction) to the concentration of many precursor species coming from both natural and anthropogenic sources. Accurate modeling of atmospheric composition requires knowing or forecasting the future evolution of these chemical forcings as well as relevant changes in climatic conditions. In the case of sufficiently large changes in atmospheric composition, interactions with resulting changes in atmospheric circulation and physical properties cannot be ignored (the chemistry of the polar stratosphere is an important case in point). Processes of particular importance for model assessments of potential atmospheric chemical composition impacts include the transport of material between the troposphere and stratosphere; the formation of aerosols and cloud particles and of their interactions with gas phase species; the natural and human-induced variability in biological sources and sinks; and the balance between chemical removal and long-range tropospheric transport.

(5) **How well can cycling of carbon through the Earth system be modeled, and t how reliable are predicted future atmospheric concentrations of carbon dioxide and methaneby these models?** To predict future climate changes and global productivity patterns, it will be necessary to develop realistic projections of the atmospheric concentrations of carbon-containing gases such as carbon dioxide and methane. These projections require understanding the interactions between the biosphere and the physical environment (especially temperature, precipitation, and carbon dioxide and methane concentrations for the terrestrial biosphere; ocean circulation for the marine biosphere; and changes in nutrients for both), as well as the basic relationships between the physical environment, human management activities (e. g. land use, fishing), and biological activity. A combination of global observation of the biosphere (including vegetation cover, above-ground biomass, and the distribution of chlorophyll in the ocean) and global biospheric models will be needed.

In order to predict how carbon cycling might change in the future, observations and representations of carbon cycling processes must be incorporated into terrestrial and oceanic ecological and biogeochemical models, as well as land cover change models. In addition, new and improved carbon cycle models will be necessary to calculate emissions for different landscapes, regions, oceans and the entire Earth system. Inverse modeling may be used to test our understanding of trace gas emissions in the light of observed atmospheric distributions and knowledge of carbon cycling processes. Such models will be important to assess our ability to simulate the past evolution of trace-gas concentrations and build up confidence in prediction capabilities for the future. The ESE will rely largely on information developed by NASA's partners in the USGCRP about future carbon dioxide emissions from fossil fuel combustion and methane emissions (e. g. from landfills, cattle, rice paddies, and natural gas production).

Table 4.6 Special Observational Requirements for Prediction and Assessments

Parameter / Question	Implementation Detail	In Situ Measurement	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Tropospheric Winds (P1)	Active Doppler lidar remote sensing	rawinsondes (NOAA, WWW)	Technical developments, demonstration needed	Very high	Commercial data purchase possible
Ocean Surface Winds (P1)	Active µwave technique	ships, buoys (NOAA. WWW)	Demonstrated by NSCAT & SeaWinds	Yes	Seawinds cooperation with Japan; EUMETSAT data acquis.
	Passive µwave radiometry/polarimetry	N/A	Windsat/Coriolis demonstration funded by DOD, USN, NPOESS	NPOESS requirement may be fulfilled	Possible
Global Precipitation (P1)	Requires 6-8 satellite constellation for Good time resolution	Rain gauges, weather radar (NOAA, WWW)	Demonstrated via TRMM and passive µwave imagers	TBD; only passive µwave currently planned	Excellent – several needed
Freeze-Thaw Transition (P1)	Need to assess in all cloud and vegetation conditions	Not a routine measurement	Awaiting demonstration	Desired; subject to operational viability	Possible
Lightning Rate (P1)	Requires geostationary implementation for temporal resolution	Sferics	Demonstrated by OTD and LIS	Could be implemented on future GOES	Possible
Soil Moisture (P1, P2)	Spatial resolution and ability to penetrate vegetation are crucial	neutron probes, lysimeters (USDA, USGS, FAO)	Approaching readiness (done from aircraft)	Highly desired, subject to operat. viability	Possible
Sea Surface Temperature (P2)	Both IR and µwave observations needed for all-weather measurement	ships, buoys (NOAA, WWW)	Excellent	NPOESS requirement	EUMETSAT coordination
Ocean Surface Topography (P2)	Prefer non-polar orbit to avoid tidal aliasing	Tide gauges; Global Geodetic Network for reference frame	Demonstrated ; development needed for denser coverage	Included on one NPOESS sat. but polar orbit is problematic	Continuation of past partnership likely
Deep Ocean Circulation (P3)	Requires *in situ* oceanographic observations	Ships and ARGO floats (NOAA, NSF)	WOCE, GODAE research projects provide initial data base	Operational Global Ocean Observing System is being envisaged	Multi-agency, international cooperation is anticipated
Total Column Ozone (P4)	High long-term accuracy needed for trend studies	Dobson, Brewer, FTIR, UV/VIS (NASA, NOAA)	Excellent	NPOESS requirement	EUMETSAT coordination
Trends in Carbon sources and sinks (P5)	CO_2 and CH_4 column mapping is most promising approach	Flask network (NOAA), Ameriflux/FluxNet (DOE, USDA, NASA)	Experimental technique; needs further development	Not currently	Possible
Land Cover/Land use Change (P5)	High spatial resolution required	Land cover maps (USGS), Veg. Inventories (DOI, USDA)	Excellent, need to reduce cost	Not currently; working with USGS	Commercial data purchase likely

5. INTRODUCTION TO NASA'S EARTH SCIENCE RESEARCH THEMES

The twenty-three research questions formulated in the previous section indicate the complexity of the global Earth environment, the multiplicity of interactions between component processes, and cross-disciplinary connections among them. In addressing these complex problems, the ESE plan for the implementation of its research programs builds on the strength of the existing Earth science disciplines, generally focused on individual components of the Earth system, which provide a common language and the background knowledge for articulating focused science questions and suggesting productive research methodologies. Thus the organization used in the following topical chapters has a strong, but not exclusive, heritage in individual Earth system disciplines, and defines research themes that each address the research questions relevant to a particular disciplinary domain. The plan identifies four environmental research themes which address four among the six topical research areas[1] of the USGCRP, and the three cross-cutting themes[2] identified by the *Research Pathways* report (NRC, 1999a). The fifth research theme, focused on the study of the Earth's interior (not part of the USGCRP) is founded on a long tradition of scientific excellence acquired by NASA since the beginning of space exploration, and has very significant applications in global satellite navigation systems, geodesy and natural hazard warning. It is important to recognize that the scientific program being implemented is derived directly from the questions enumerated in the previous section.

Although the organization used in the topical chapters reflects principal components of the Earth system, it is critical to emphasize the importance placed within ESE on interdisciplinary science. ESE has a strong research program designed to address interdisciplinary questions, and the Earth system science perspective is being increasingly utilized in the development of the research program.

1. Biology and Biogeochemistry of Ecosystems and the Global Carbon Cycle

This component focuses on the study of change in the Earth's terrestrial and marine ecosystems and biogeochemical cycles. It addresses ecosystems as they are affected by human activity, as they change due to their own intrinsic biological dynamics, and as they respond to climatic variations and, in turn, affect climate. Research approaches range from detailed process-level studies, to global-scale observations of productivity and carbon sources and sinks, and to mechanistic modeling of ecosystem dynamics and biogeochemical cycling processes. Emphasis is on characterizing the processes that affect the Earth's capacity for biological productivity, documenting changes in land cover and land use, understanding the role of the biosphere in Earth system function, and quantifying changes in the global carbon cycle, especially major fluxes and the active land, ocean, and atmospheric reservoirs..

2. Atmospheric Chemistry, Aerosols and Solar Radiation

The research theme encompasses the processes responsible for the emission, uptake, transport, and chemical transformation of ozone and precursor molecules associated with its production in the troposphere and its destruction in the stratosphere, as well as the formation, properties, and transport of aerosols in the Earth's troposphere and stratosphere (the direct impact of aerosols on atmospheric radiation transfer and effects on cloud formation and properties are discussed in the subsequent chapter on the global water and energy cycle). Since variations in solar activity have considerable influence on

[1] Biology and Biogeochemistry of Ecosystems, Change in the Climate System on Seasonal-to-Interannual and Decadal-to-Centennial Timescales, Change in the Chemistry of the Atmosphere.
[2] Global water cycle, global carbon cycle, and the climate prediction, including the role and impacts on humans.

atmospheric composition and chemistry, the monitoring of solar radiation (both total irradiance and spectrally-resolved irradiance) is also included.

3. Global Water and Energy Cycle

The principal research objective is to explore the connection between weather processes and climate change and the fast dynamical/physical processes that govern climate responses and feedbacks. Particularly significant is the transformation of water among its three physical states – vapor, liquid, and ice - in the atmosphere and at the surface of the Earth. The condensation of water in cloud and snow control both the albedo and radiation balance of the planet, and the constant renewal of fresh water resources. The development of weather system, the cloud life cycle and their role in the water and atmospheric energy cycles are approached as a single integrated problem. Another central science objective is exploring the responses of hydrologic regimes to changes in climate (precipitation, evaporation, and surface run-off) and the influence of surface hydrology (soil moisture, snow accumulation and soil freezing) on climate.

4. Oceans and Ice in the Earth System

The research theme is principally focused on the slower processes that affect the distribution of large liquid and solid water masses on the planet, the circulation of the Earth's oceans and the mass balance of glaciers and ice-sheets. The oceans and ice-sheets are driven by atmospheric forces: ocean surface wind, changes in ocean water buoyancy brought about by air-sea fluxes of radiation, heat and fresh water (precipitation minus evaporation), sea-ice formation and melting, and snow accumulation on ice surfaces. or snowfall. The research objective is to understand and model the dynamics of the oceans and ice, on all space- and time-scales that are relevant to the dynamics of the coupled ocean-atmosphere system and sea-level rise. Relatively short period and small-scale phenomena associated with upper ocean and coastal zone variability may also be studied, recognizing that process-level knowledge is necessary for predicting the behavior of coupled climate system, for understanding oceanic biological productivity and biogeochemistry, and for many marine applications.

5. Solid Earth Science

This ESE research theme contributes to knowledge in two broad domains of Earth sciences: inferring from observation the motions of the Earth and Earth's interior, and observing how the Earth surface is being transformed as a means to predict future change. The former aims to provides the fundamental knowledge basis for understanding the Earth dynamics (e. g. the precise shape of Earth and its gravity field) as well as supporting a broad range of modern applications (e. g. space-based navigation systems). The latter aims to establish the conceptual and observational framework for assessing the risks associated with natural hazard, such as earthquakes, volcanic eruptions and landslides. On a more fundamental level, the solid Earth science program contributes to understanding how the forces generated by the dynamism of the Earth's interior have shaped landscapes and driven the chemical differentiation of the planet, including recent processes such as volcanic eruptions.

M. Earth System Modeling

The ultimate challenge of Earth system science is to consolidate the scientific findings in the different disciplines into an integrated representation of the coupled atmosphere, ocean, ice, land and biosphere system. This matter is the topic of the final synthesis chapter on Earth System

Observation and Modeling. The hallmark of the ESE program is the integration of observations with model representations: observational data sets without an explicative model provide little insight in the nature of the underlying mechanisms; models without observation provide no verifiable conclusion. Coupled Earth system models are the tool of choice for predicting future variations and trends in the Earth system, most notably that of the Earth's climate system, but including evolution of its chemical and biological components. Such models also provide tools that can be used to contribute to science-based assessments of potential future changes. Data assimilation systems provide a framework for combining global observations with models in order to provide geophysically consistent data sets as well as optimal initial multi-parameter fields which can be used for the improvement of predictive capability, including the initialization of forecast models used for short- to intermediate-term simulation. While models of individual components are described within the relevant topical research themes above, the chapter focuses on modeling research and data assimilation development aiming to investigate the interaction among these components and predict transient variations and trends in the coupled system, such as climatic oscillations (ENSO, NAO, etc.) and longer-term climate change under various forcing scenarios.

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CHAPTER 2

BIOLOGY AND BIOGEOCHEMISTRY OF ECOSYSTEMS AND THE GLOBAL CARBON CYCLE

2.0 INTRODUCTION

Earth's ecosystems are being subjected to human intervention and environmental changes on an unprecedented scale, in both rate and geographical extent. The ability of human societies to ameliorate, adapt to, or benefit from these rapid changes requires fundamental knowledge of the responses of terrestrial and marine ecosystems to global change (IGBP, 1992). Also required is an understanding of the implications of these changes for increased food production, sustainable resource management, and the maintenance of a healthy, productive environment. As human societies seek to develop policies that respond to the impacts of global change, there will be a continuing requirement for objective, scientific information to understand the current impacts and predict the future effects of such policies. Presently, there is an urgent need for information on sources and sinks of carbon in the environment and on the capacity of terrestrial and marine ecosystems to store carbon dioxide released to the atmosphere as a result of human activities.

NASA research on the biology and biogeochemistry of ecosystems and the global carbon cycle aims to understand and predict how terrestrial and marine ecosystems are changing. This research theme addresses ecosystems as they are affected by human activity, as they change due to their own intrinsic biological dynamics, and as they respond to climatic variations and, in turn, affect climate. Emphasis is on understanding the processes of the Earth system that affect its capacity for biological productivity and on the role of the biosphere in Earth system function. Documenting and understanding changes in land cover and land use are priorities. Understanding the distribution and cycling of carbon among the active land, ocean, and atmospheric reservoirs constitutes a major scientific focus for research as well as a new priority for interagency cooperation and international assessment (USGCRP, 1999).

2.1 SCIENCE QUESTIONS

How are global ecosystems changing? (Question V3)

Terrestrial and marine ecosystems are subject to change from natural variability in the environment, their own internal biological dynamics, and changes brought about by human activities. Changes occur in virtually all aspects of the environment, including atmospheric composition, the deposition of nutrients, incident solar radiation, climate, land use and fishing practices, and biodiversity. More subtle, though no less important, changes are occurring in the temperature and circulation of the ocean. Many of these environmental components are not only varying, but are trending or increasing in rate or amplitude of variation. Thus, it is vitally important to be able to discriminate between those variations related to intrinsic dynamics and the variability of the global environment and those that are caused by human actions and which therefore may result in significant changes in the state and future evolution of ecosystems. We will need to document the spatial distribution and extent, temporal dynamics, and productivity of Earth's ecosystems in order to provide a baseline against which to evaluate future change.

What changes are occurring in global land cover and land use, and what are their causes? (Question F2)

Changes in the Earth's land cover and land use are pervasive and increasingly rapid; few landscapes are unaffected. The causes of change in land cover and land use arise from a combination of human (social, economic, policy) and biophysical (biogeochemical, hydrologic, climatic) factors. Changes in land use and land cover resulting from the need to feed an expanding human population will constitute the most important forcing on terrestrial ecosystems over the next several decades (IGBP, 1997). Knowing which landscapes are changing and how they are changing will be important for optimal food production, natural resource management, biological conservation, and carbon monitoring. We will need consistent and reliable information on changes in land cover and land use over periods of years to decades. Quantifying vegetation recovery from past land clearing will be critical for assessing terrestrial carbon sinks. We also will need to understand the causes of land cover and land use change, including both human actions and climatic factors, in order to predict future changes (IGBP/IHDP, 1995).

How do ecosystems respond to and affect global environmental change and the carbon cycle? (Question R2)

The Earth's ecosystems are experiencing widespread disturbance, novel environments, and exploitation by an increasing human population. There are great uncertainties in our understanding of how present-day ecosystems respond, and this makes predicting how they will respond to future changes a major scientific challenge (NRC, 1994). Improved ecological information on the responses of ecosystem distribution, structure, and physiological and biogeochemical function to global environmental change will be essential to meeting this challenge. Changes often occur in interacting combinations, and we need improved understanding of how ecosystem components and functions respond to multiple stresses (NRC, 1999) and disturbances. We can anticipate some environmental changes that may occur in the future, such as altered precipitation patterns or increased frequency of extreme weather events, but others may surprise us. It is vitally important to investigate the implications of such changes for sustained agriculture, forestry, and fisheries, and for the continued provision of ecosystem goods and services that are valuable to human societies. There also are significant uncertainties regarding the responses of ecosystems as they, in turn, feedback to control fluxes of water, energy, and trace gases. Determining the magnitude of these effects will be important for assessing impacts on climate and atmospheric composition (IPCC, 1996).

Carbon is the basic constituent of all biological systems. Along with the oceans and the atmosphere, the biosphere is one of three active global carbon reservoirs. Through the processes of photosynthesis, respiration, and decomposition, marine and terrestrial ecosystems cycle carbon among these reservoirs. Atmospheric carbon dioxide concentrations have been increasing over the past 250 years, This increase is primarily caused by fossil fuel burning and forest clearing, and constitutes the largest anthropogenic contribution to the planetary greenhouse effect and the potential for climate change. Increasing atmospheric carbon dioxide levels also can stimulate photosynthetic carbon fixation in terrestrial plants (an effect often referred to as carbon dioxide fertilization) and may result in increased carbon storage in terrestrial ecosystems. Forest clearing releases carbon to the atmosphere and subsequent regrowth takes up carbon dioxide, but the net effect on regional carbon storage over time is not clear. The oceans also take up carbon dioxide, but the strength of this sink, its evolution over time, and the interaction with the ocean's planktonic ecosystems are equally unclear. Recent studies indicate the global biosphere must be storing significant amounts of anthropogenic carbon dioxide each year, thus, reducing the total amount remaining in the atmosphere, yet we do not know where this carbon is going or how long the storage can persist. We need to understand the past and present roles of ecosystems in storing carbon and to predict their future role under a range of scenarios (Sarmiento, et al., 1999). A complete understanding of the carbon cycle will require knowledge of its interactions with the nitrogen, phosphorus, and sulfur cycles; with other trace nutrients; and with the water cycle.

What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity? (Question C2)

Changes in land cover and land use have impacts and implications at local, regional, and global scales because of the way they alter Earth system biophysical, biogeochemical, and hydrological states and processes. These changes affect agricultural, forest, and water resources; biodiversity; carbon storage or release; and the geographic distribution and activities of human populations. We need quantitative information on the consequences of land cover and land use change, including changes in productivity patterns, land degradation, intensified management, and loss of biodiversity; changes in the storage and fluxes of important biogeochemical elements, especially carbon and water; and increased inputs of pollutants, nutrients and sediments to coastal oceans. Future estimates of greenhouse gas emissions, assessments of climate change impacts, and evaluation of land management practices and possible mitigation strategies will depend upon information on the consequences of land cover and land use change. An ability to realistically model ecosystems undergoing land use change will be critical to the success of these endeavors. Ultimately, this research must provide the scientific underpinning for sustainable management of the natural resources of our planet.

What are the consequences of climate and sea level changes and increased human activities on coastal regions? (Question C3)

Coastal regions are extremely vulnerable to severe weather events and sea-level rise, and they are increasingly disturbed by human activities. Land cover and land use changes within the drainage basins of the rivers feeding into coastal regions are major sources of sediments, nutrients, and pollutants to coastal ecosystems. Rapid growth in coastal populations poses additional severe pollution risks. Understanding the consequences of these human activities, in combination with the effects of global climate change and sea-level rise (see also 6.3.4 of Solid Earth chapter), will be needed for effective resource management in the coastal zone and for us to mitigate effectively or adapt to the changing coastal environment.

How well can cycling of carbon through the Earth system be modeled, and how reliable are predicted future atmospheric concentrations of carbon dioxide and methane by these models? (Question P5)

Reliable estimates of future atmospheric concentrations of carbon-containing greenhouse gases are needed to evaluate potential global environmental changes. To be able to predict future atmospheric concentrations of carbon dioxide, we must understand the mechanisms that control the carbon cycle, including how they interact with each other and with the environment. Only by accurately representing carbon cycle processes in models can we hope to produce realistic projections of future atmospheric concentrations. New and improved models must be developed and rigorously tested. We need improved models of ecological and biogeochemical cycling that calculate carbon uptake and emissions based on remote sensing observations and point data from *in situ* networks. We need models to extend these results across landscapes, regions, ocean basins, and the entire Earth system. We need models to simulate scenarios of change over time and that can produce credible predictions. For methane, we also need improved atmospheric chemistry models and to establish linkages between them and ecosystem and biogeochemical cycling models (see also Chapter 3, Atmospheric Chemistry, Aerosols, and Solar Radiation). Current climate models do not incorporate a dynamic understanding of the carbon cycle, and are not able to reproduce patterns of variability in, for example, source and sink regions for carbon dioxide. Advances must be made toward the development and implementation of dynamic, coupled models of the land-atmosphere, ocean-atmosphere, land-ocean, and land-ocean-atmosphere systems to achieve realistic carbon cycle portrayals. These new models also should be capable of evaluating alternative scenarios for management of carbon.

To answer these questions, NASA will pursue a strategy combining remote sensing observations with *in situ* observations, basic research, process studies, and modeling. These activities will focus on integrating and extending knowledge across spatial and temporal scales, and on predicting ecosystem responses to global environmental change. The desired outcomes include:

- scientific assessments of specific ecosystem responses to potential environmental changes and quantitative carbon budgets and emissions estimates of key global ecosystems for decision-making purposes;
- fundamental understanding of primary productivity and the consequences of land cover and land use change as a basis for applications to agriculture, forestry, fisheries, sustainable land and marine resource management, and biodiversity conservation; and
- information on ecosystem interactions with the atmosphere that can be used to improve weather and climate prediction and to assess impacts on atmospheric chemistry.

2.2 NATURE OF THE PROBLEM AND SCOPE OF THE PROGRAM

Planet Earth offers the only opportunity to study living systems and the processes of life. The present Earth system is the result of the coupled evolution of life and the planet. It is the product of interactions among the biosphere, hydrosphere, atmosphere, and geosphere over billions of years. On Earth, the basic chemical constituents of organic matter, carbon, nitrogen, oxygen, phosphorus, and sulfur, follow a closed loop or cycle through increasing energy states, as they are incorporated into living tissue, and then decreasing energy levels as the tissues decompose, giving rise to the biogeochemical cycles. These biogeochemical cycles are an expression of life and the signature of a living planet.

The ecosystems of Planet Earth are an essential foundation for human societies – they are, quite simply, our life support system. People depend on ecosystems for an extensive variety of goods and services. Food, forage, fiber, timber, construction materials, and pharmaceuticals exemplify the goods. Services include the maintenance of water resources, air quality, soil fertility, fisheries, wildlife habitat, and biodiversity. Climate regulation and recreational opportunities are considered other types of services. Healthy ecosystems strengthen economies and make sustained use possible; damaged ecosystems weaken economies and pose severe challenges for continued use.

For the first time in history, the actions of one species – humans – are changing atmospheric composition, climate, hydrology, land cover, and soils at unprecedented rates globally. Population growth, increasing levels of consumption by society, and changes in technology and socio-political organization are responsible for these accelerated environmental impacts (IGBP, 1997). Nearly half the population of the world resides in coastal regions, and the coastal ocean is increasingly disturbed by human activities. Marginal lands with limited soil fertility or water resources are supporting more people. Continued population growth can only increase pressure on the Earth's resources.

Since the beginning of the Industrial Revolution, human activities have significantly altered biogeochemical cycling, and the magnitude of human disturbance may be approaching a critical level: the concentrations of atmospheric carbon dioxide and methane are moving into ranges without historical precedent. Recent policy debates have demonstrated the need to quantify sources and sinks of carbon dioxide and other greenhouse gases on national, regional, and continental scales and to predict how these sources and sinks might change in the future.

Human agricultural, urban, and industrial activities have had similar impacts on the nitrogen, phosphorus, and sulfur cycles. The increased availability of these nutrients is especially important for understanding regional productivity patterns and global carbon stocks. Excess nutrients are reaching and affecting aquatic systems such as groundwater, wetlands, lakes, rivers, estuaries, and the coastal ocean. The global carbon, nitrogen, phosphorus, and sulfur cycles are interlocked, and perturbations in one will have impacts on the others. These perturbations constitute an ongoing biogeochemical experiment at the global level, and raise serious questions for all societies.

Thus, the NASA Earth Science Enterprise (ESE) contribution to the study of life in the universe focuses on understanding change in the Earth's ecosystems and biogeochemical cycles and on predicting future changes and their consequences at time scales relevant to humans. This research addresses major objectives of the U.S. Global Change Research Program's (USGCRP) Biology and Biogeochemistry of Ecosystems program element and its Carbon Cycle Science initiative. It also forms the core of ESE's contribution to NASA's cross-Enterprise program in Astrobiology. Current and future ESE research to address the six science questions identified in section 2.1 targets the following major topic areas: global primary productivity, land cover and land use change, ecosystem responses and feedback processes, and the global carbon cycle.

2.2.1 Global Primary Productivity

Photosynthetic carbon fixation by terrestrial plants and marine algae, referred to as primary productivity, is the basic energy capturing process that fuels nearly all life on Earth. Net primary productivity (NPP) is the measure of productivity left after losses due to plant respiration are subtracted. Roughly half (55%) of global NPP occurs on land, resulting in the storage of carbon in the form of plants, plant litter, and soil organic matter. The remainder (45%) takes place in the oceans, due almost entirely to the life cycle of phytoplankton (single-cell algae) in the upper illuminated layer. As phytoplankton photosynthesize, the partial pressure of carbon dioxide in the surface ocean becomes under-saturated relative to the atmosphere, thus drawing carbon dioxide from the atmosphere into the ocean; this is the so-called "biological pump".

Changes in NPP and its global distribution are of great concern because of the direct consequences for human and animal food supplies. For agriculture, forestry and fisheries, the harvestable fraction of this total NPP (i. e., yield) is the relevant measure of productivity. Both NPP and yield are amenable to estimation using satellite data. For questions of carbon cycle dynamics, net ecosystem productivity (NEP) and net biome productivity (NBP) are the measures needed. NEP is obtained by subtracting from NPP the losses of carbon due to heterotrophic respiration and decomposition processes within the ecosystem. NEP may be either positive or negative and is determined by the balance between photosynthetic uptake (which increases with atmospheric carbon dioxide, although at a diminishing rate) and losses due to respiration and decomposition (which increase at an increasing rate with temperature). NBP is NEP summed across the full spatial extent of a given biome, accounting for landscape heterogeneity.

Factors that can increase NPP include recovery from past disturbances and management practices; favorable changes in climate; and nutrient fertilization resulting from atmospheric deposition, oceanic circulation and upwelling, or agricultural application (nitrogen and phosphorus are most important in terrestrial ecosystems, and nitrogen, iron, and other trace elements are most important in marine ecosystems). Carbon dioxide fertilization, in combination with its effect of increased water use efficiency, can also increase NPP in terrestrial ecosystems, but the net effect on NEP and carbon storage of this direct forcing of carbon dioxide on photosynthesis in combination with its indirect forcing through increasing temperature on respiration and decomposition is not well-understood. Factors that can decrease NPP include nutrient limitations, the dissemination of toxic pollutants, urban encroachment on arable lands, poor management practices, and unfavorable climatic changes.

2.2.2 Land Cover and Land Use Change

Distribution and Extent of Land Cover and Land Use Change

Today, a consistent, global-scale database of land cover and/or land use change over the last 200 years does not exist. This period is particularly important because the global population increased ten-fold, population density in several regions increased by more than 100 times, and agriculture replaced natural vegetation in large parts of North America, China, and India. Even more surprising, perhaps, is that there is no consistent, high resolution, global land cover time series data product for the past 20 years of satellite remote sensing. Progress in understanding how humans are changing the Earth is partially stymied by this lack of consistent information on land cover and land use change. There is a strong need to mine the existing record of high resolution satellite imagery to provide a baseline of land cover change and its impacts, and to ensure that these changes are more consistently documented and assessed in the future.

Causes of Land Cover and Land Use Change

To understand the consequences of land cover and land use change, both the biophysical and the human factors that cause land cover and land use changes must be addressed. The demand for food to feed an increasing world population will force further conversion of natural ecosystems to agriculture and the intensification of production on currently cropped lands. Other changes in land cover are expected to occur due to changes in forest exploitation, and, possibly, due to afforestation measures attempting to sequester carbon from the atmosphere. Natural and human-induced disturbances such as fire, insect infestations, and logging change large areas of the Earth's surface, but more subtle changes that result in habitat degradation and fragmentation are also important because they lead to diminished ecosystem functionality and loss of biodiversity.

Consequences of Land Cover and Land Use Change

Quantifying the impacts of land cover and land use change on carbon sources and sinks will be critical to understanding the overall response of the carbon cycle to human activities. One of the main driving factors responsible for current carbon uptake on land may be land use, both past and present. Widespread reforestation of agricultural lands, as has been occurring since 1900 in the eastern U.S., and increased productivity on remaining agricultural lands has led to increased carbon storage in forests and soils. On the other hand, clearing of forests for agriculture in other parts of the world, for example in tropical forest regions, is releasing carbon to the atmosphere. We need accurate estimates of the regional and global effects of historical and current land use change and land management practices on carbon sources and sinks.

Land cover and land use change constitute the primary contributor to the loss of biodiversity at all levels (genes, species, and ecosystems). Human-introduced invasive species and pathogens are also changing the biodiversity of the planet. The majority of the Earth's species reside in the humid tropics, and these species-rich areas are undergoing the most rapid rates of human population growth accompanied by economic development -- two factors that have traditionally led to the rapid conversion and loss of natural land cover. While land cover can on occasion be restored, a lost species and its unique genotype and role in an ecosystem are lost forever. In order to understand the true nature and extent of ongoing biodiversity loss, information is needed on the rate and magnitude of conversion of natural land cover at local to global scales.

Changes in land use will result in increasing stress on riverine and coastal ecosystems. Near-shore embayments, estuaries and wetlands are the spawning and nursery grounds for many fish species. Coastal regions are susceptible to over-fertilization by nutrient-rich river discharge and atmospheric deposition, with consequent depletion of oxygen (hypoxia) and widespread fish mortality. Increases in phytoplankton concentrations or sediment loads pose a threat to coral reef ecosystems, which thrive only in very clear tropical waters.

2.2.3 Ecosystem Responses and Feedback Processes

Ecosystem Responses to Environmental Change

Ecosystem responses to environmental change can occur on a wide range of time scales and may involve changes in physiological or biogeochemical functions, and/or changes in distribution and structure (e. g., species composition, biomass distribution, canopy architecture). Forcings of change can be broadly categorized as stresses, which are often chronic in nature, and physical disturbances, which tend to be episodic.

Physiological processes will dominate short-term responses to change. They control the accumulation or loss of biomass, the cycling and storage of key nutrients, and the exchanges of energy, water, and trace gases with the atmosphere. In terrestrial ecosystems, these processes are affected in a complex, interactive way by forcings from changes in atmospheric carbon dioxide, land use practices, temperature, rainfall, and incident solar radiation. A principal objective is to acquire quantitative information about canopy and land surface biophysical or biochemical properties that characterize important physiological processes. This information is needed to drive ecological models and has proven to be indispensable in scaling them up for regional and global applications as well as in scaling down global models. In marine ecosystems, phytoplankton population turnover rates are governed by changes in the supply of light and nutrients, and can be as short as 1-2 days. Wind mixing and vertical stratification of the upper ocean, thermohaline (density-driven) circulation, nutrient deposition by rainfall and dust, and cloudiness are some of the forcing factors. Carbon dioxide is not a limiting factor in the ocean.

On longer time scales, changes in the composition and structure of both terrestrial and marine ecosystems will dominate. Such changes may include changes in the geographic distribution and extent of terrestrial and ocean ecosystems, as well as changes in the species composition of their communities. We know that ecosystems are not necessarily in equilibrium with their physical and chemical environment, that stress response thresholds exist, and that abrupt transitions from one type of ecosystem to another are possible. Better representation of the relevant processes and forcing factors is needed for the next generation of ecosystem models in order to capture the nature of these transitions and predict future responses. Observations to track both the occurrence of and the recovery from major disturbances (e.g. fire, introduction of invasive species, insect infestations, deforestation) are critical for understanding terrestrial ecosystems. Moreover, chronic stresses (e.g., grazing, nitrogen deposition) that cause slower changes in structural and biogeochemical dynamics will require observations of variability and trends over periods of many years.

We have yet to understand shifts in ecosystem structure and function that have been known to occur rapidly and persist for decades, with significant impacts on biogeochemical cycling and the availability of food and other natural resources. Ecosystem responses may have lag times of decades or longer or they may occur only when certain critical thresholds are exceeded. Such phenomena, if not accounted for in predictions, have the potential to cause surprises for which human societies are unprepared. More realistic ecosystem models are needed to handle such effects.

Ecosystem Feedback to Atmospheric Chemistry and Climate

Ecosystems play a significant role in modifying the atmosphere. They are sources and sinks of trace gases, including the greenhouse gases that control climate. Methane is of particular concern because the cause(s) for its recent increase in concentration in the atmosphere are not identified (i. e., known sources and sinks do not balance the global methane budget), nor do we understand the interannual variations in atmospheric methane concentrations. Fires, which occur due to natural climate-related causes as well as human actions, release to the atmosphere large pulses of carbon dioxide and other trace gases, as well as extensive amounts of soot and carbonaceous aerosols. Biogenic sources of nitrous oxide, a greenhouse gas, and methyl bromide, both of which play a role in stratospheric ozone depletion, are significant.

Terrestrial vegetation directly influences the global water cycle and also affects atmospheric circulation through changes in evapotranspiration, surface albedo, and roughness and, consequently, surface temperature, the stability of the atmospheric boundary layer, precipitation, and weather. Many ecosystems recover from disturbance or environmental stress slowly and retain a memory of the past stressful conditions, thereby introducing significant time lags in ecosystem response to climate variability and in subsequent feedback to the climate system. Changes in land cover and land use can result in large changes to surface properties. The amount of forcing these changes can exert on the total Earth system is currently not known. Sensitivity studies with altered land cover distributions in general circulation models have shown that drastic changes in land cover may lead to significant feedbacks to atmospheric circulation. In addition, regional climate simulations have shown that important teleconnections may exist whereby changes in one region may cause a change in climate conditions in other, less disturbed areas.

Rapid feedback to the climate system is possible in ocean ecosystems because phytoplankton populations turn over quickly. One potential feedback mechanism between oceanic biological productivity and climate involves the effect of precursor compounds (e.g., dimethyl-sulfide and dimethyl-sulfonium propionate) produced by oceanic phytoplankton that generate sulfur-based aerosols. These aerosols act as cloud condensation nuclei and the resulting clouds reduce the transmission of photosynthetically active radiation and increase planetary albedo, thus introducing a negative feedback to biological productivity and a cooling effect on climate.

2.2.4 The Global Carbon Cycle

Estimates of the net anthropogenic carbon budget for 1980-1989 are shown in Table 2-1. The annual mean carbon budget requires an inferred sink to balance known sources, but the exact nature of the sink(s) is not known. The latitudinal distribution of sources and constraints on inter-hemispheric transport of carbon dioxide point to the existence of two sinks. The larger sink is in the Northern Hemisphere (where the largest sources are located) and thought to be in terrestrial ecosystems; a smaller sink, likely associated with oceanic biogeochemical processes, is thought to exist in the Southern Ocean (Sarmiento et al., 1999). The sources and sinks with greatest relative uncertainty in Table 2-1 are associated with land use and land cover change, and oceanic uptake. The oceans are, without question, a net sink for anthropogenic carbon dioxide, but the strength of this sink is unclear, and the sensitivity of the biological pump to environmental change is not well-understood. In terrestrial ecosystems, forest clearing is a source of carbon to the atmosphere, but subsequent secondary regrowth of natural vegetation after clearing due to fire or abandonment of agricultural lands can result in rapid uptake of carbon dioxide; the net carbon balance of such recovering ecosystems, especially over a full successional cycle, is not well-understood. More subtle, are uncertainties related to the possible changes in carbon storage resulting from carbon dioxide fertilization of terrestrial ecosystems, changes in other global biogeochemical cycles, and/or changes in the physical climate system. Understanding the global carbon cycle will be key to comprehending ecosystem change and to developing a reasonable range of scenarios of future atmospheric concentrations of carbon dioxide and other greenhouse gases for use in Earth system models.

The international Framework Convention on Climate Change calls for limitation of the annual net emissions of six greenhouses gases, including carbon dioxide, by the years 2008-2012. Significant sinks such as reforestation may be accounted for as negative emissions to offset sources. Thus, many nations are beginning to consider how best to develop national inventories of carbon emissions and to evaluate enhanced carbon storage in their ecosystems. Considerably improved measurements of fluxes and better understanding of natural sources and sinks will be required for a nation to conduct such carbon accounting, let alone adhere to any agreed-upon protocols. The possibility for ecosystems to absorb significant amounts of carbon dioxide, thus slowing the accumulation of carbon dioxide in the atmosphere, is a key issue in the debate on carbon dioxide emission controls. If terrestrial ecosystems can be managed for this purpose, it becomes imperative to learn how long this capability can be maintained and whether it can be increased. There is also growing interest in iron fertilization of marine productivity as a method of stimulating carbon sequestration. Recent experiments in the Equatorial Pacific and the Southern Ocean confirm the effect, but more research is needed to understand the ecological consequences and effectiveness of the approach.

TABLE 2-1

Anthropogenic Carbon Budget for 1980-89 (IPCC, 1995)

(Units are GtC/yr; uncertainties are 95% Confidence Limits)

Carbon Dioxide Sources		
(1)	Emissions from fossil fuel combustion and cement production:	5.5 ± 0.5
(2)	Net emissions from changes in tropical land use:	1.6 ± 1.0
(3)	Total anthropogenic emissions [(1)+(2)]:	7.1 ± 1.1
Partitioning Among Reservoirs		
(4)	Storage in the atmosphere:	3.3 ± 0.2
(5)	Ocean uptake:	2.0 ± 0.8
(6)	Uptake by Northern Hemisphere forest regrowth:	0.5 ± 0.5
(7)	Inferred sink [(3)- {(4)+(5)+(6)}]:	1.3 ± 1.5

2.2.5 Strategy and Program Plan for Biology and Biogeochemistry of Ecosystems and the Global Carbon Cycle Theme

Overall Strategy

NASA ESE research on the biology and biogeochemistry of ecosystems and the global carbon cycle requires a coordinated national and international effort to acquire global data sets and assess the effects of global environmental change. NASA's contribution is focused on providing data and information derived from space-based remote sensing systems capable of observing the Earth's ecosystems at multiple scales and across the full range of the electromagnetic spectrum. Both moderate and high spatial resolutions and frequent repeat observations are required. Airborne and *in situ* observations, intensive field campaigns, process studies, data and information systems, and models are equally important to NASA's contribution because they are absolutely essential for interpreting and making full use of satellite observations. The strategy is to realize an optimal balance among systematic and exploratory measurements from space, airborne and *in situ* observations, basic process studies, case studies, modeling, and integrative data analysis. It is to be expected that this balance will change as scientific understanding and technological capabilities evolve and as space missions advance from the conceptual stage through flight and data analysis.

Priorities for Satellite Missions

The post-2002 mission planning process assigned high priority to the systematic observations that will fulfill the need for continuous records of biospheric state and activity to address questions of decadal-scale variation in ecosystems. Measurements of ocean color, terrestrial vegetation biophysical properties, and land cover provide the critical foundation for addressing all of the science questions highlighted in this chapter. They support research on natural variability of the biosphere, forcings of the Earth system by land cover change, response of ecosystems to changes, and assessment of consequences for human societies. These data sets also are needed as critical inputs for ecological, biogeochemical, and land cover change models, including those that predict future changes to the Earth system. The major challenge for NASA is to ensure that these global measurements continue in such a way as to promote scientific continuity, while encouraging the evolution of instrument and other mission technologies at reasonable costs.

For the foreseeable future, mission concepts that offer the most significant advances toward understanding and quantifying global carbon cycle dynamics, including the distribution and composition of land cover, will receive the highest priority. Mission concepts that address impacts caused by disturbance and anthropogenic stresses on marine and terrestrial ecosystems and on their sustainability will receive next highest priority. Proposed exploratory missions are described in the section on program elements (section 2.3). Other ideas for exploratory missions will, no doubt, arise as both scientific understanding and technological capability advance. Investments in basic preparatory science and technology development will be made to advance the most promising concepts, and then decisions as to which mission(s) to pursue will be made at an appropriate time based on peer review and with due consideration of other scientific, programmatic, national, and international priorities (see section 1.3, Overview). Commitments to the pursuit of a new type of exploratory science mission will be made only after the technology has been evaluated and the new measurement capability has been assessed for scientific validity and the potential to answer a critical global change question.

Planning for Field Campaigns and Modeling

The development and approval processes for space-flight missions necessitate a detailed strategic plan of specific missions that will be scientifically compelling and technologically feasible in a 5-10 year time frame. However, flexibility is paramount for planning future field campaigns and process studies as well as for deciding upon the next steps in modeling and integration. It is not uncommon for scientific priorities to shift as breakthroughs occur and attention to turn rapidly from reducing one major scientific uncertainty to addressing the next. Field campaigns and process studies can have maximum impact by responding to these advances, and, therefore, benefit from a flexible and near-term planning and commitment process within the context of an on-going research and analysis program. The same is true for identifying the next steps in modeling. Thus, these components of the implementation plan for biology and biogeochemistry of ecosystems and the global carbon cycle do not have rigidly defined plans for the period after 2005.

The process for identifying future science-driven field campaigns requires a dialogue within the ESE research community that leads to a scientific consensus on the priority problem or problems to target. ESE priorities, logistical and cost considerations, and national and international partnerships are then factored into NASA’s decision as to which field campaign to pursue. Consultation and coordination with other national and international research sponsors throughout the planning and implementation process is essential. Interactions with IGBP’s core projects are particularly valuable. Inclusion of scientists from the region of a field campaign has clear benefits and is expected. Definition of satellite validation-driven field campaigns is usually conducted by the satellite instrument science team or by a validation science team selected through a separate competitive process. In the future, field campaigns that strongly integrate science and satellite validation objectives will receive priority.

Essential Interactions

The scientific research agenda for NASA research on the biology and biogeochemistry of ecosystems and the global carbon cycle is heavily influenced by the scientific recommendations, plans, and initiatives of the U.S. National Academy of Science, the U.S. Committee on Environment and Natural Resources (CENR), and the International Geosphere-Biosphere Programme (IGBP). The CENR Subcommittee on Global Change Research (USGCRP) provides the primary forum for setting scientific priorities and coordinating research and scientific assessment activities with other U.S. agencies, but there is also interaction with the CENR Subcommittee on Ecological Systems. Opportunities to collaborate with other space agencies also influence this research agenda.

Research on the biology and biogeochemistry of ecosystems and the global carbon cycle is closely intertwined with that of the other research themes within the ESE, especially given the importance of cross-disciplinary research for advancing Earth system models – which are the common tools needed to predict future global changes and their consequences for societies. In addition, there is a strong linkage to ESE Applications programs, with emphasis on extending understanding of global productivity patterns to agricultural, forestry, and fisheries applications; developing the scientific basis for new applications of satellite data; supporting national and international environmental vulnerability assessments; and addressing the consequences of ecosystem disturbances from such natural hazards as fire, flooding, oil spills, and extreme weather.

This research agenda intersects with that of NASA's cross-Enterprise research program in Astrobiology. ESE leads research efforts aimed at the Astrobiology goal of: "determining how ecosystems respond to environmental change on time scales relevant to human life on Earth." Research within the biology and biogeochemistry of ecosystems and the global carbon cycle theme also supports other Astrobiology goals through (1) research on microbiology (related to controls on nutrient cycling and trace gas emissions), (2) development of Earth system models that simulate the co-evolution and adaptation of life and the changing environment, and (3) research to characterize the signals of life that can be remotely sensed for Earth.

Overall Program Plan

Systematic Observations

Understanding how ecosystems vary over time (Question V3), respond to global environmental change (Question R2), and affect the global carbon cycle (Question R2) requires consistent time series of satellite observations of global ocean color, vegetation properties, and land cover. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Moderate-Resolution Imaging Spectro-radiometer (MODIS) of the Earth Observing System (EOS), the Global Productivity Mission, and the Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies (SIMBIOS) project (see Ocean Ecology and Biogeochemistry (OEB) program element, section 2.3.1.1) fulfill the need for ocean color data to produce estimates of ocean primary productivity and to drive models of ocean carbon dynamics. The Advanced Very High Resolution Radiometer (AVHRR), MODIS, and the Global Productivity Mission (see Terrestrial Ecology and Biogeochemistry (TEB) program element, section 2.3.2.1) fulfill the need for moderate spatial resolution vegetation indices and biophysical properties to produce estimates of terrestrial primary productivity and to drive models of terrestrial carbon dynamics.

Understanding how land cover and land use are changing and also identifying causes and consequences (Questions F2 and C2) primarily require the consistent time series of high spatial resolution satellite observations of global land cover provided by the Landsat 7 and Land Cover Inventory Mission (see Land Cover and Land Use Change (LCLUC) program element, section 2.3.3.1). Additionally, AVHRR, SeaWiFS, EOS, and the Global Productivity Mission (see OEB and TEB program elements, sections 2.3.1.1 and 2.3.2.1) provide useful moderate spatial resolution information on global land cover and on the consequences of land cover and land use change. Landsat 7 and the Land Cover Inventory Mission also provide the needed high spatial resolution land cover and coastal data to assess local to regional scale carbon storage and fluxes and to drive local- to landscape-scale process models of carbon dynamics (Question R2). These systematic missions and measurements are discussed more fully in section 2.3.

Exploratory Observations

There is a strong need for exploratory satellite remote sensing estimates of above-ground biomass (i.e., terrestrial carbon stocks) and information on vegetation response and biomass recovery following disturbance which will be addressed by the Vegetation Canopy Lidar (VCL) mission and the proposed Vegetation Recovery Mission, respectively (see TEB, section 2.3.2.2). These data are needed to reduce uncertainties related to carbon storage in regrowing vegetation (Question R2) and to investigate the consequences of land cover and land use changes caused by disturbance (Question C2). A Cold Climate Land Surface Processes research mission may provide accurate estimates of growing season length and the timing of the spring thaw at high latitudes in order to improve estimates of annual carbon uptake for those regions (Question R2). If sufficiently precise measurements of atmospheric carbon dioxide concentrations could be made from space, such observations would be of high priority for quantifying global sources and sinks of carbon (Question R2) and predicting future atmospheric carbon dioxide concentrations (Question C3; see TEB, section 2.3.2.2). These proposed future exploratory missions and measurements are discussed more fully in section 2.3.

In situ Observations and Process Studies

Field campaigns, *in situ* observations, case studies, and process studies will be conducted (1) to investigate comprehensively ecosystem responses to multiple stressors and disturbances (Questions F2, C2, R2, P5, and C3), (2) to investigate in detail the forcings and consequences of land cover and land use change in the regions of the world experiencing the most change or where anthropogenic stresses are likely to increase most rapidly (Questions F2, C2, and C3), and (3) to understand better the controls on carbon uptake and release by global ecosystems, to understand the effects of interrelated changes in nitrogen, phosphorus, iron and other trace nutrients, and to improve local, national, and regional carbon budget and emissions estimates (Questions R2 and P5).

Modeling

Research to improve ecological, biogeochemical, carbon budget, and land use models will be a priority, as will be research to develop a next generation of coupled land-atmosphere, ocean-atmosphere, land-ocean, and, ultimately, land-ocean-atmosphere models.

Expected Scientific Achievements

In the next decade, the NASA ESE expects to contribute substantially to our understanding of the biology and biogeochemistry of ecosystems and the global carbon cycle and the practical implications of changes in these systems and processes for human societies. NASA ESE research on the global carbon cycle will be fully integrated into the USGCRP's new Carbon Cycle Science program where NASA expects to play a leadership role in providing global satellite observations of carbon sources and sinks, estimating global primary productivity, and developing new space-based measurement capabilities. The satellite observations, field campaigns, case studies, process studies, and modeling activities detailed in section 2.3 have been planned to produce the scientific achievements summarized in Table 2-2.

TABLE 2-2

Expected Scientific Achievements

Question V3: How are global ecosystems changing?

Expected new knowledge in the next 5 years

- Year-to-year variations in global marine primary productivity quantified;
- Year-to-year variations in global terrestrial primary productivity quantified.

Expected new knowledge in the next 10 years

- Decadal variability in ocean primary productivity;
- Relationship between year-to-year variations in net primary production and agricultural and forest productivity at regional scales.

Question F2: What changes are occurring in global land cover and land use, and what are their causes?

Expected new knowledge in the next 5 years

- First quantitative inventory of global forest cover based on Landsat data;
- Global inventory of land cover and analysis of land cover change based on Landsat data, establishing a basis for periodic assessments of global land cover change;
- First ecological, biogeochemical cycling, and land use model simulation results incorporating actual land cover observations;
- Global inventory of fire occurrence.

Expected new knowledge in the next 10 years

- Quantitative assessments of global land cover change on 5 year periods;
- Predictive, coupled socio-economic and ecological models of land cover and land use change;

Question R2: How do ecosystems respond to and affect global environmental change and the carbon cycle?

Expected new knowledge in the next 5 years

- First global estimates of carbon stocks in forests derived from satellite data;
- Quantitative evaluation of coupled land-ocean-atmosphere carbon cycling models;
- Estimation of the efficiency of photosynthetic carbon uptake in marine ecosystems globally;
- First estimates of vegetation height distribution and vertical structure from a space-based lidar sensor, and evaluation of derived estimates of above-ground biomass in forests.
- Process-level and system-level understanding of the effects of deforestation and agricultural use on tropical ecosystems and the implications for sustainable use of Amazonian ecosystems;
- Fully interactive ecosystem-climate models for simulations to evaluate climate change scenarios;
- Ability to identify phytoplankton groups from satellite imagery;
- Analysis of regional trace gas and aerosol emissions from fire.

Expected new knowledge in the next 10 years

- Prediction of the magnitude of carbon export to the deep ocean, and assessment of its sensitivity to environmental factors;
- First quantitative, globally consistent estimate of the rate and amount of carbon uptake in ecosystems responding to disturbance (i.e., secondary forest growth, re-forestation, recovery from stress or catastrophic events);
- Credible estimates of annual carbon uptake and storage in key land regions of the Northern Hemisphere.

Question C2: What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?

Expected new knowledge in the next 5 years

- Evaluation of the utility of remote sensing imagery for assessing the impacts of land cover and land use change on biodiversity.

Expected new knowledge in the next 10 years

- Regional assessments of the consequences of land use change and a first global synthesis;

Question C3: What are the consequences of climate and sea level changes and increased human activities on coastal regions?

Expected new knowledge in the next 5 years

- An accurate map of the extent of coral reefs in the global ocean;
- Discrimination of phytoplankton from detrital material in the coastal ocean;
- Establishment of relationships between ocean processes and fish populations in coastal upwelling regimes.

Expected new knowledge in the next 10 years

- First predictions of the occurrence of harmful algal blooms in coastal waters;
- Quantitative estimates of the exchanges of materials between the land and the coastal ocean.
- Quantitative estimation of coral reef structure from airborne or space platforms

Question P5: How well can cycling of carbon through the Earth system be modeled, and how reliable are predicted future atmospheric concentrations of carbon dioxide and methane by these models?

Expected new knowledge in the next 5 years

- Coupled land-atmosphere model predictions of carbon dioxide fluxes from terrestrial ecosystems.

Expected new knowledge in the next 10 years

- Coupled land-ocean-atmosphere model predictions of carbon dioxide fluxes and concentrations in the atmosphere;
- Coupled land-atmosphere model predictions of methane fluxes from terrestrial ecosystems, including wetlands.

2.3 NASA PROGRAM ELEMENTS

The Earth Science Enterprise (ESE) program elements under the theme of Biology and Biogeochemistry of Ecosystems and the Global Carbon Cycle are:

- Ocean Ecology and Biogeochemistry (OEB);
- Terrestrial Ecology and Biogeochemistry (TEB); and
- Land Cover and Land Use Change (LCLUC).

Each includes:

- Systematic Global Observations;
- Exploratory Satellite Observations;
- Field Campaigns and Process Studies; and
- Modeling and Integration.

These program elements encompass ESE scientific research and analysis programs and major NASA investments in the EOS Terra, EOS Aqua, and Landsat 7 missions; the Earth System Science Pathfinder (ESSP) Program; the New Millennium Program (NMP); and the Instrument Incubator Program (IIP); advanced data and information systems, such as the EOS Data and Information System (EOSDIS), the Earth Science Information Partners (ESIP) federation experiment, and the New Data and Information System and Services (NewDISS); and commercial data purchases.

2.3.1 OCEAN ECOLOGY AND BIOGEOCHEMISTRY (OEB)

The goal of NASA research in ocean ecology and biogeochemistry is to understand the physical and biological controls on primary productivity in the ocean, and to predict how marine ecosystems will respond to, and affect, environmental change.

This program element addresses the variability of marine ecosystems (Question V3), their role in the global carbon cycle (Question R2), and their responses to and effects on global environmental change (Question R2). The consequences of land cover and land use change in the coastal ocean (Questions C2 and C3) are also addressed.

The primary approach is comprised of:

- acquisition of a multi-year global ocean productivity database;
- studies of relevant biological, chemical, and physical processes; and
- development of both process-resolving and global ecosystem models.

Within the above approach, NASA's program in Ocean Ecology and Biogeochemistry has several objectives to be accomplished over the next 10 years:

- assembly of a long-term time-series of ocean color;
- identification of taxonomic groups of phytoplankton from space;
- discrimination of the absorbing and scattering components in coastal water;
- understanding the biological dynamics of the coastal ocean; and
- measuring the depth variability of biological properties of the upper ocean.

Satellite measurements of ocean color are the only source of global information on ocean primary productivity and its response to a variety of factors. The experimental Coastal Zone Color Scanner (CZCS) instrument on Nimbus-7 (1978-1986) first demonstrated quantitative estimation of the concentration of chlorophyll, which can be used as an index of phytoplankton biomass. The chlorophyll measurement is related in a complex way to primary productivity in the surface ocean.

Time-Series of Ocean Color and Natural Variability

While the physical and biological controls on primary productivity are generally understood qualitatively, it remains a problem to quantify and model natural variability in marine ecosystems. It is even more challenging to model these complex physical-biological processes in order to predict the consequences of environmental change. Large-scale transient climate anomalies such as El Niño are, in effect, natural experiments that provide the opportunity to develop and test such predictive biological-physical models. To develop and test models of the biological responses to changes occurring over long time periods requires sustained systematic global measurements of ocean color, together with contemporaneous satellite measurements of relevant physical parameters, including wind stress, ocean dynamic height, and sea surface temperature (see Chapter 5, Ocean and Ice in the Earth System). The acquisition of time series of measurements of ocean color, and therefore, ocean productivity, over decadal time scales, is the fundamental step in understanding the response of ocean ecosystems to global climate change.

Oceanic Forcing

Ocean biological processes cannot be understood without considering the physical processes acting on them. Progress toward understanding global ocean productivity, as revealed by the time series of ocean color measurements, is critically dependent upon contemporaneous global observations of physical variables and processes. This calls for the continuation of systematic satellite observations of dynamic topography (ocean circulation), sea-surface temperature, surface winds, and incident solar radiation, as well as the development of new capabilities such as remote sensing of surface salinity (see section 5.3.1). Emerging areas of interdisciplinary research in remote sensing that NASA will exploit involve the use of ocean color variability to indicate physical phenomena, such as circulation and upwelling, and the use of dynamic topography and winds to estimate productivity.

Responses of Phytoplankton Taxonomic Groups

Recent research indicates that carbon cycling within the euphotic layer depends upon plankton community structure. Where the community is comprised of very small phytoplankton, the phytoplankton are immediately grazed by zooplankton, and organic matter is recycled rapidly, with very little carbon sinking to the deep ocean. Export of organic carbon occurs instead following the seasonal and episodic blooms of larger phytoplankton such as diatoms. Thus, a key to understanding carbon cycling in the ocean is to know what controls blooms. Other functional phytoplankton groups play specific roles, such as the production of calcium carbonate or the fixation of nitrogen. Identifying the factors that control the distribution of such key phytoplankton groups is a central scientific goal. The role of functional groups in biogeochemical cycling, and their responses to different climatic and anthropogenic forcings, can be evaluated with coupled biological-physical models. To provide an observational basis for testing these models, methods will be established for identifying major functional groups from space.

The relationship of planktonic ecosystems to the biogeochemistry of the upper ocean and to atmospheric phenomena is another area targeted for future ESE research. Much of the equatorial and northern Pacific Ocean and the Southern Ocean have low chlorophyll levels throughout the year despite ample supplies of the major nutrients (e.g., nitrate and phosphate). It is believed that iron is the critical missing element in these so-called "high nutrient, low chlorophyll" (HNLC) regions. Even in regions of high chlorophyll content, such as coastal upwelling areas, iron or other micronutrients may ultimately limit productivity. Dust particles carried by winds from African, South American, and Asian deserts are thought to be significant sources of iron for the open ocean. HNLC regions do not currently receive iron from these sources, but changes in atmospheric circulation or desertification might alter the transport of mineral dust with major consequences for oceanic productivity. Experimental additions of iron to the ocean show that the effects are on the larger phytoplankton. Thus, this biogeochemical process affects community structure and, therefore, the ocean's carbon cycling. Other oceanic regions are limited by the availability of fixed nitrogen, supplied by the atmosphere and rivers. Human activities have increased atmospheric nitrogen deposition by as much as a factor of two, and this flux is likely to increase in the future.

Consequences in the Coastal Ocean

. Coastal waters and continental shelves are the most productive areas in the ocean. They support major industries (fisheries, tourism, oil and gas) and constitute the Exclusive Economic Zone (EEZ) which legally extends national boundaries 200 nautical miles seaward. It is estimated that nearly 70% of the U.S. population will live in coastal counties by the year 2020 and similar trends are projected for the world's population. Rapid growth in coastal populations carries severe pollution risks, and calls for effective resource management. Indeed, increased attention is already being paid to phenomena such as harmful algal blooms (WHOI, 1995), coastal and estuarine eutrophication, sea level rise, tsunamis, and hurricanes, all of which have accentuated impacts in coastal zones. For NASA, the major issues in the coastal zone are (1) interpreting satellite imagery for Case-2 waters (i.e., waters containing significant amounts of terrigenous and other non-living material that affects their color) and (2) understanding the dynamics of the coastal ocean. Retrieval of the chlorophyll signal in the presence of the other absorbing substances in Case-2 waters is a current research challenge. Creation of a chlorophyll algorithm for satellite imagery of the coastal ocean will be the first step toward understanding the biological dynamics of the coastal zone. Addressing these issues will enable research applications on fisheries problems, eutrophication, the destruction of coral reefs, and the occurrence of nuisance and harmful algal blooms. Harmful algal blooms also come under the category of natural hazards, in that they affect fisheries, human health, and recreational uses of the coastal zone. This demonstrates a linkage to the ESE Applications Program’s natural hazards research.

Depth Variability of Biological Variables

Satellite imagery shows the spatial variability of biological and physical properties of the ocean, but satellites miss an important component of ocean variability: that is, variation with depth. The ocean's mixed layer depth is a critical factor in the evolution of both physical and biological properties, and therefore important to evaluation of remotely sensed data. For much of the ocean, chlorophyll exhibits strong vertical structure, characterized by a maximum at some distance below the surface. By delineating the vertical distribution of planktonic ecosystems, predictive models of the ocean's carbon cycle will become more accurate. NASA will investigate the feasibility of obtaining such observations with aircraft-based oceanographic lidar instruments, and will conduct basic research that could lay the foundation for future space-based observations.

2.3.1.1 Systematic Global Observations for Ocean Ecology and Biogeochemistry

The highest priority requirement for ecological research in the ocean is to assemble a long-term record of global ocean chlorophyll and productivity measurements. The existing time series, which establishes the variability in the ecosystem, began with the CZCS (1978-1986). After a 10-year hiatus, it was resumed with the Ocean Color and Temperature Scanner (OCTS, 1996-1997), and then with SeaWiFS (launched in 1997). Global ocean color observations will continue with MODIS on the EOS Terra and Aqua spacecraft, the Medium Resolution Imaging Spectrometer (MERIS) on the European Environmental Satellite (ENVISAT), and the Global Imager (GLI) and Polarization and Directionality of Earth’s

Reflectance (POLDER) instruments on Japan's Advanced Earth Observing System (ADEOS-2) satellite. Other ocean color sensors include the Modular Optoelectric Scanner (MOS, a German-Indian collaboration) and India's Ocean Color Monitor (OCM). In collaboration with national and international partners, NASA plans to combine ocean color measurements from existing and future satellite missions to produce a coherent, long-term time-series of global oceanic primary productivity data spanning several decades. NASA is a sponsor of the International Ocean Color Coordinating Group (IOCCG), an affiliate organization of the international Scientific Committee on Oceanic Research (SCOR), which provides a forum for the exchange of information and technical guidance on ocean color measurements between space agencies with current or planned ocean color satellite missions. NASA also participates in the International Global Observing Strategy (IGOS) partnership involving the Committee on Earth Observation Satellites (CEOS) other international organizations.

The ESE plan for continuing acquisition of moderate spatial and spectral resolution imaging radiometer data is to promote the convergence of operational observation requirements with the scientific requirements of the EOS program. In the long-term, NASA plans to rely on the measurements acquired by the next-generation imaging sensor (see Box 1) on the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The transition from EOS global imaging to the NPOESS program will be assured by a bridging mission (see Box 3) covering the intermediate period 2005-2009.

Box 1
Global Productivity Mission

In the long term, NASA's nominal plan is to rely on the NPOESS program for systematic moderate resolution imaging of the Earth surface and atmosphere. Consultations between NASA and the NPOESS Program Office are underway to develop a Visible and Infrared Imaging Radiometer Suite (VIIRS) that could fulfill the observation needs of both scientific and operational users. A joint bridging mission (NPOESS preparatory project) is planned in 2005 to fly a prototype of this instrument and ensure observation continuity between EOS and the first NPOESS mission in 2008-2009 (See also Box 3).

Spatial resolution on the order of 250 –1000 m is required for monitoring terrestrial and marine productivity, vegetation type, phenology, cloud cover, fire occurrences, and snow and ice cover. Frequent observation (revisit time on the order of 1-2 days) is essential to capture relatively rapid changes (time scales on the order of a week) that occur during a growing season. Spectral channels similar to those provided by MODIS are required in order to retain similar basic retrieval algorithms and deliver products compatible with EOS records.

The satellite data analysis project primarily associated with systematic observations is the SIMBIOS Project. SIMBIOS was initiated in 1997 to address specifically the challenge of merging ocean color data from different sensors. SIMBIOS must rely on *in situ* measurements (optical and biological properties of the ocean and atmospheric observations) for calibration of satellite observations and validation of remote sensing products. As additional ocean color data sets become available, the SIMBIOS project will continue to conduct intercomparisons of sensor characteristics and retrieval algorithms, and improve calibrations. The ESE will maintain optical instruments at several mooring sites for calibration and validation of satellite ocean color instruments, including the Marine Optical Buoy (MOBY) located off the Hawaiian Island of Lanai, and will help support long-term optical moorings sponsored by other agencies or countries. As part of the SIMBIOS program, NASA co-sponsors validation cruises with other countries.

2.3.1.2 Exploratory Satellite Missions for Ocean Ecology and Biogeochemistry

Despite progress in ocean color remote sensing, as demonstrated with SeaWiFS, the derivation of oceanic primary productivity and the study of biogeochemistry from space is still very much information-limited. Currently, satellite sensors measure only a snapshot of the reflective and radiative properties of the ocean at a few wavelengths; and there is no information regarding depth. Promising remote sensing technologies now in development and new data products from global optical imagers (to be launched in 2002-2005) are expected to meet these limitations. These new technologies include (1) hyperspectral remote sensing, (2) the measurement of fluorescence properties of surface waters, (3) oceanographic lidars, and (4) imaging of episodic variability. In addition to these new technologies, there is also a need for improved atmospheric correction techniques in coastal regions as well as the open ocean. This effort will benefit from new remote sensing technologies for measuring atmospheric aerosols (see Chapter 4 on Atmospheric Chemistry, Aerosols, and Solar Radiation), and new developments in modeling the optical properties of absorbing aerosols and mineral dust. There is also interest in a proposed atmospheric carbon dioxide mission for identifying and quantifying oceanic carbon source and sink regions (see TEB, section 2.3.2.2).

Hyperspectral Observations and Data Analysis

Very-high spectral resolution (~10 nm) imaging spectrometers allow the discrimination of various components in seawater, including the identification of key taxonomic or functional groups of phytoplankton. Phytoplankton are classified based on their pigment composition, and the different pigments have characteristic absorption maxima. If the different pigments can be discriminated using space-based spectrometers, then the structure of the phytoplankton community can be estimated. Likewise, coccolithophore blooms can be detected by the anomalously high reflectance of their calcite covering. Nitrogen fixers also may be identified through their specific pigment signatures. Improved spectral and spatial resolutions will lead to new techniques for detecting harmful algal blooms and for mapping and monitoring coral reef ecosystems.

Coral reefs occupy a potentially significant fraction of the tropical ocean, but estimates of their areal extent vary by an order of magnitude. NASA plans to map the Earth's coral reefs in a hierarchical manner, using a combination of space-based sensing, aircraft missions, and *in situ* studies. Large-scale mapping, encompassing the tropics for example, will be done at low resolution (1-4 km) using the satellite sensors for ocean color (SeaWiFS, MODIS). Landsat 7 (see LCLUC, section 2.3.3.1) is collecting relevant high-spatial resolution data (30 m) over selected coral reefs. A major part of the effort will be to develop hyperspectral techniques for identifying reef structures, classifying types, and monitoring reef health. Hyperspectral sensors are available on aircraft, and will be used in conjunction with *in situ* studies.

Both NASA and other groups plan to deploy hyperspectral imagers in the near future. The NMP Earth Observing-1 (EO-1) technology demonstration mission was launched in November, 2000. The Department of Defense (DOD) also has plans for experimental hyperspectral imaging missions. NASA will continue to utilize airborne hyperspectral sensors, such as the Airborne Visible Infrared Imaging Spectrometer (AVIRIS), over coastal waters and coral reefs. Although MODIS and GLI are moderate spectral resolution sensors, they do have a few very narrow spectral bands that will provide insight for future experimental hyperspectral endeavors.

Fluorescence Properties

MODIS (on EOS Terra and Aqua) and the Global Imager (GLI) on ADEOS-2 will have detectors (sensitive in the red part of the spectrum) for measuring phytoplankton fluorescence. This is an important development in at least two respects. First, fluorescence is a property of phytoplankton only. Thus, in coastal, Case-2 waters, where ocean color observations are confounded by other absorbing components, the phytoplankton can be measured in a different way, and therefore the productivity of coastal waters can be estimated with greater accuracy. Second, the ratio of fluorescence to chlorophyll (where the amount of chlorophyll can be estimated), the "fluorescence yield," provides an indication of the physiological condition of the phytoplankton, and, thus, can be used to increase the accuracy of productivity estimates that are otherwise based on chlorophyll alone.

Vertical structure

Lidars offer the possibility of measuring the vertical structure of the upper ocean in terms of hydrographic as well as biological structure. Oceanographic lidars are currently being evaluated as aircraft-based instruments. The results of these studies will be used to guide future ESE technology investments that could advance such observations for consideration on satellite missions in the latter part of this decade.

Event Imaging

Ocean color satellites generally provide global imagery at time scales, typically, of a week, and miss important dynamics. There are processes in biological and physical dynamics of the ocean that occur on time scales of hours to days. Tidal cycles are important for coastal ocean dynamics, and resolving the tidal cycle is a critical requirement that can only be fulfilled by at least hourly observations from a geostationary platform. Understanding of changing coastlines and coral reefs would also benefit by monitoring at high temporal resolution. There are two missions that will support dynamical studies in coastal regions. First, the "Special Events Imager" (SEI) has been proposed as a joint NASA-NOAA operational prototype sensor to provide event imaging capability on GOES geostationary satellites (Kennel et al, 1999). The SEI will offer, for the first time, the study of very short time-scale ocean dynamical processes at specific locales. Second, the International Space Station’s (ISS) Window Observational Research Facility (WORF) is being considered for mounting hyperspectral sensors to monitor change and study dynamics in coastal and coral reef ecosystems. ISS can revisit desired sites daily and has other operational characteristics (such as instrument turn-around), that can make it a more efficient means of collecting data than a free-flying satellite.

2.3.1.3 Field Campaigns and Process Studies for Ocean Ecology and Biogeochemistry

Field campaigns for ocean ecology and biogeochemistry are conducted to validate data retrieved from satellite sensors. They may be designed, for example, to provide data over a range of environmental variability in order to establish algorithms for converting the color of the ocean to plant pigment values quantitatively. Field campaigns are a major component of the SIMBIOS project. After a satellite is launched, a complete suite of ocean optical measurements is needed for initial validation of the satellite sensor. Later in the life of the sensor, validation cruises are required to characterize sensor degradation, or to aid in the development of improved algorithms.

Process studies conducted from ships are needed to understand the linkage between physiological and biogeochemical processes, which take place at very short time and space scales, and the optical properties of the water. They are important for putting the satellite observations into an oceanographic context. The strategy aims to progress beyond empirical or statistical relationships between *in-situ* and remote-sensing measurements, and achieve a more mechanistic or theoretical understanding.

Coordination of shipboard and satellite studies is mutually beneficial: satellite data extend shipboard measurements in space and time, and shipboard research allows interpretation of large-scale satellite observations in terms of oceanic processes. With the exception of calibration/validation cruises in support of a particular satellite sensor, NASA does not normally sponsor ship-based research campaigns, but supports the participation by individual U.S. scientists in campaigns sponsored by other agencies or research institutions. NASA's role is primarily to provide satellite or airborne remote sensing data in support of these major campaigns.

In the past, NASA has supported investigators in the Joint Global Ocean Flux Study (JGOFS), the Ecology and Oceanography of Harmful Algal Blooms Program (with NOAA, NSF, EPA, and ONR), and the Coastal Intensive Site Network (with EPA and NOAA). There are three candidate programs on the ocean's carbon cycle, successors to JGOFS that are now in the planning stage, with which NASA will likely cooperate in the future. SOLAS (Surface Ocean - Lower Atmosphere) will focus on fluxes across the air-sea interface. OCTET (Ocean Carbon Transformations, Export and Transfers) has a more biogeochemical orientation, and will center on carbon and nutrient fluxes throughout the ocean's water column. EDOCC (Ecological Determinants of the Ocean's Carbon Cycle) will focus on the effect of ecosystem dynamics on the carbon cycle. NASA plans to participate in planning these programs to understand the ocean's carbon cycling dynamics, to offer guidance in terms of satellite and airborne missions, and to participate in implementation of process studies. Another way in which NASA supports process studies is by coordination with international partners through the IOCCG and the IGOS partnership.

In addition, NASA will support at-sea process studies of the role of phytoplankton as sources of methyl bromide and dimethyl sulfide compounds, and of the influence of such emissions on atmospheric chemistry and climate. Research in this area is expected to provide a basis for combining satellite-derived phytoplankton and physical data to estimate natural sources of these gases.

2.3.1.4 Modeling for Ocean Ecology and Biogeochemistry

Ocean ecology and biogeochemistry are at the heart of pressing environmental and social problems, and the scientific community will increasingly be asked to produce predictive models of demonstrable skill. For example, in the coastal zone, society will need to know potential outcomes and hazards associated with development and resource exploitation. Both predictive and diagnostic models will be used in the development of system models for the coastal zone (land-ocean models) and for the open ocean (ocean-atmosphere models). Over the next decade, NASA will participate in the development of coupled land-ocean-atmosphere models.

Modeling of ocean ecosystems is limited by the availability of observations covering large regions, and the continued availability of extensive marine observations, feasible only with satellites, is crucial for continued model development. We are not yet able to reproduce the variability of the surface ocean in models, and this reflects our lack of understanding of the forces affecting biological variability. In terms of the global carbon cycle, a major unknown is the magnitude and variability of the biological pump which has a significant impact on the distribution of carbon as well as the other elements. In this regard, models of the carbon cycle will, of necessity, have to include interactions with phosphorus, nitrogen, silica, and iron.

NASA will assist in the development of data assimilation schemes and coupled biological-physical models to link surface ocean color measured by satellites to the underlying physical dynamics in order to capture the dynamical behavior of phytoplankton communities over the full depth of the euphotic zone. These models will be extended to include effects on higher trophic levels, including those relevant to fisheries (NRC, 1992).

The overall objective is to be able to combine the time series of observations (aided by calibration and validation field campaigns), process studies, and new types of remote sensing measurements, to obtain a better understanding of the ocean's carbon cycle. These studies must be linked to studies of the physical processes that force, and the chemical processes that are affected by, biological dynamics. Heat fluxes and wind drive changes in biological processes and carbon dioxide fluxes in the surface ocean. Phytoplankton growth and decay affect the ocean's chemistry, and also that of the overlying atmosphere. Models test our understanding of these relationships, and NASA will generate models, validate their output at global scales, and predict future outcomes for the environment.

2.3.2 TERRESTRIAL ECOLOGY AND BIOGEOCHEMISTRY (TEB)

The goal of ESE's terrestrial ecology and biogeochemistry research is to improve understanding of the structure and function of global terrestrial ecosystems, their interactions with the atmosphere and hydrosphere, and their role in the cycling of the major biogeochemical elements and water.

This program element addresses variability in terrestrial ecosystems (Question V3), their role in responding to and affecting global environmental change (Question R2) and in the global carbon cycle (Questions R2 and P5). Land cover and land use change (Questions F2 and C2) are not addressed directly, but are considered among the forcings to and responses of ecosystems.

The research approach combines:

- use of remote sensing to observe terrestrial ecosystems and their responses;
- field campaigns and process studies to elucidate ecosystem function; and
- ecosystem and biogeochemical cycling models to predict responses.

Current research emphasizes analysis of:

- ecosystem responses to change;
- terrestrial productivity;
- carbon cycling; and
- land-atmosphere interactions and feedback to climate and atmospheric chemistry.

Ecosystem Responses to Change

The USGCRP is currently highlighting a need to understand the responses of ecosystems to multiple stresses, including the combined impacts of changes in climate (e.g., changes in the frequency and occurrence of extreme events), air and water pollution, atmospheric carbon dioxide concentration, and nutrient availability (USGCRP, 1999; NRC, 1999). Response to disturbance is an area of growing priority as well. The research strategy to understand the effects of multiple, interacting environmental stresses and disturbances on ecosystems includes field campaigns to acquire comprehensive data sets, fundamental process studies, and manipulative field experiments to quantify the integrated effects of multiple changes (e.g., free-air carbon dioxide enrichment experiments combined with nutrient or moisture manipulations). ESE field campaigns are conducted to provide the needed comprehensive data sets, as well as certain process studies. Other agencies will lead in conducting other process studies and the needed manipulative field experiments. NASA will limit its involvement in such experiments to support of remote sensing-oriented activities using its unique observing capabilities. In general, ESE will support analyses of space-based observations of ecosystem responses, especially time series of data, to document large-scale response patterns and derive understanding of the processes of change. In addition, ESE will support model development activities that incorporate responses to multiple stresses.

Terrestrial Productivity

Research to observe and understand patterns of change in global primary productivity will continue to be an ESE priority because of its direct relevance for understanding food production, ecosystem health, and the global carbon cycle. Patterns of terrestrial NPP vary greatly from region to region and from year to year, as recent regional food surpluses and famines illustrate dramatically. Daily, seasonal, and annual primary productivity can be monitored from space using spectroradiometers sensitive to visible and near-infrared wavelengths. Terrestrial productivity is characterized in terms of vegetation indices or relationships with remotely sensed biophysical properties, such as the leaf area index (LAI) or the fraction of absorbed photosynthetically active radiation (fAPAR). Analysis of vegetation development over the course of a growing season provides useful estimates of annual NPP and yields, as well as predictions of food shortages. ESE plans to continue producing global data sets of vegetation indices and biophysical properties as a means of estimating primary productivity, with increased emphasis on quantitative analysis of data from a new generation of satellite sensors.

Carbon Cycling

The new USGCRP initiative on Carbon Cycle Science seeks information on the fate of carbon in the environment, including the partitioning and exchanges of carbon among the various active reservoirs, and carbon transfer between the terrestrial biosphere and the atmosphere caused by human activities (USGCRP, 1999; Sarmiento, et al., 1999). ESE will contribute to this initiative by leading in the provision of satellite-based estimates of primary productivity, documentation of the global distribution of carbon sources and sinks, and exploration of new remote-sensing methods for inferring above-ground biomass or measuring other carbon cycle components. New satellite observations of fire occurrence, spatial extent, and temperature will provide an observational foundation for analyzing biomass loss due to fire and related trace gas emissions to the atmosphere. ESE will partner with other agencies in the conduct of process studies and the development of improved global and regional carbon cycle models.

Land-Atmosphere Interactions

Research on land-atmosphere interactions supports ESE studies of land hydrological processes and atmospheric chemistry in order to advance integrated Earth system science. With regard to climate and the global water cycle, the objective is to understand how changes in ecosystem properties and processes affect factors such as surface albedo and net radiation, the partitioning between latent and sensible heat fluxes, aerodynamic roughness, boundary layer properties, and aerosol emissions, and, thus, control exchanges of energy, water, and particulate matter. Of particular interest is how knowledge of these interactions can be used to improve weather forecasts and climate predictions. Cooperation with the Global Water and Energy Cycle program element (see Chapter 2) is important for these interactions. ESE's terrestrial ecology and biogeochemistry program element will investigate these interactions and feedback mechanisms through satellite data analysis, major field campaigns, and improvements to interactive Earth system component models.

With regard to interactions with atmospheric chemistry, research in terrestrial ecology and biogeochemistry will emphasize quantitative understanding of emissions of radiatively and chemically important trace gases and particulates from terrestrial ecosystems. The redistribution and deposition of nutrients by the atmosphere is also of interest. Coordination with the Atmospheric Chemistry program element (see Chapter 4) is important in this regard. Actual observation of trace gas emissions and nutrient deposition, and relevant process studies fall within the responsibilities of other USGCRP agencies (NSF, EPA, DOE, USDA). However, NASA has contributed by developing *in situ* measurement technologies and supporting trace gas observations and process studies in the field -- primarily of methane and nitrous oxide. Future efforts will be focused on improving estimates of regional and global trace gas emissions and carbon and nitrogen budgets using enhanced data analysis methods and models. Satellite observations of fires will provide an observational foundation for assessing releases of trace gases and particulates to the atmosphere. Trace gas observations and process studies will be conducted primarily in the context of major field campaigns.

Consequences

A difficult scientific challenge is to quantify the implications of terrestrial ecosystem changes for sustained provision of food, fiber, and ecological services in the face of a growing human population, climatic variations, and other environmental stresses. Changes in the productivity, carbon storage, biodiversity, and health of both managed and unmanaged ecosystems can have significant implications for local, regional, and global economies and for the quality of life. Research in this domain will be pursued in cooperation with the ESE Applications programs (e.g., joint research on productivity and the impacts of fires), as well as other government agencies, to deliver information needed for environmental assessments and decision-making.

2.3.2.1 Systematic Global Observations for Terrestrial Ecology and Biogeochemistry

Observations of terrestrial ecosystems at fine spatial and fine temporal resolutions are required to address the science questions for terrestrial ecology and biogeochemistry. High spatial resolution data are required to characterize ecosystem processes and responses to environmental changes at a spatial scale close to that at which the causal factors operate and the initial responses occur. High temporal resolution data are required to capture short-term physiological responses, phenological events, and interactions with the changing environment, and, in the case of optical sensors, to increase the frequency of cloud-free observations. Since a single satellite instrument combining high spatial and high temporal resolutions remains beyond current technical capabilities, the observational strategy is based on simultaneous deployment of instruments with inversely related spatial and temporal resolutions. Thus, the highest priorities for satellite observations are for continued systematic global measurements of (1) vegetation indices and biophysical properties at moderate spatial resolution (0.5–1 km) with near-daily sampling frequency, and (2) land surface multispectral reflectance at high spatial resolution (30 m) as frequently as possible (now about 16 days).

Moderate spatial resolution, high temporal frequency data will be used to generate and improve global estimates of terrestrial productivity and carbon sequestration, to characterize phenology, and to analyze changes over time. Global data sets are needed also for use in Earth system models and to validate model predictions. These observations will extend the time series started in 1981 with Advanced Very High Resolution Radiometer (AVHRR) measurements on NOAA's polar orbiter series and continued with MODIS measurements on the EOS Terra and Aqua missions. Major advances in quantitative retrieval of vegetation and surface biophysical properties are expected from the improved performance, characterization, and absolute calibration of the MODIS instrument. NASA's plan for continuation of these observations is to cooperate with NOAA and the DOD to effect the convergence of the research and operational observation programs in this area and, eventually, rely on NPOESS and other future global operational observing systems. A single bridging mission, the NPOESS Preparatory Project, carrying the first VIIRS instrument is needed to fill the 2005-2009 gap between MODIS and the first NPOESS VIIRS flight.

High spatial resolution data will be used in support of local- to regional-scale process studies and field campaigns and for quantitative analysis of terrestrial ecosystem changes and carbon cycle components. The high spatial resolution observations will extend the time series started in 1972 with Earth Resources Technology Satellite 1 (Landsat 1) and continued today with Landsat 7. Other high spatial resolution optical and microwave observing systems provide complementary information and will be used to enhance temporal sampling, mitigate cloud cover problems, or incorporate new information. A series of land imaging missions following Landsat 7 is required. Each mission would carry an instrument capable of producing multispectral (visible through short-wave infrared) imagery at fine (~10-30 m) spatial resolution and of obtaining global coverage seasonally. The instrument concept for the next such mission could be based on the Advanced Land Imager design being tested on the NMP EO-1 technology demonstration mission. In order to meet continuity requirements, this mission would need to be launched in 2005.

Data analysis priorities for the next 3-5 years will focus on exploiting MODIS and Landsat 7 data, and on assuring that these new data sets can be tied to historical records from AVHRR and the Landsat 1-5 sensors. In the 5-10 year time frame, the highest priority for new, systematic satellite observations is to ensure the continuity of these two global data records. Close coordination with potential operational or commercial data providers will be essential to ensuring mutually beneficial partnerships. Use of data from foreign missions (e.g., MERIS, GLI, various SAR instruments) will be necessary to fill gaps and enhance data products. Details of the planned systematic observation missions are provided in Boxes 1 and 2 (see sections 2.3.1.1 and 2.3.3.1, respectively).

2.3.2.2 Exploratory Satellite Missions for Terrestrial Ecology and Biogeochemistry

The need to quantify the carbon cycle, assess patterns of biomass change, and understand ecosystem responses to disturbance drives the requirements for future exploratory satellite missions. Missions focused on these specific objectives have been proposed (Kennel et al., 1999), as well as innovative exploitation of new satellite observations provided by the EOS program in order to explore a broader range of potential ecological and biogeochemical applications.

Vegetation Canopy Lidar Mission

Measurement of biomass from space would enable greatly improved estimates of terrestrial carbon storage as well as agricultural and forest yields for a variety of practical applications. The ESSP VCL mission proposed to fly an array of five laser altimeters to measure canopy top heights, the vertical distribution of leaves and branches, and ground surface topography over portions of the Earth’s surface. The height and vertical distribution of vegetation canopies will be used to generate estimates of above-ground biomass and carbon storage. In the next 2-5 years, ESE-sponsored research on this topic will focus on developing methods for estimating canopy structure and above-ground biomass in support of quantitative analysis of the global carbon cycle.

Vegetation Recovery Mission.

Quantifying the rates, patterns, and degree to which landscapes respond to both anthropogenic and natural disturbance will address a major uncertainty in the terrestrial carbon budget, that is, carbon uptake by secondary, regrowing forests. For this purpose, it will be critical to track, in terms of above-ground biomass, both the occurrence of and recovery from such major disturbances as clear cutting and fires. A proposed post-2002 exploratory research mission to quantify biomass recovery addresses this need (Kennel et al., 1999). The nominal Vegetation Recovery mission measurement strategy requires periodic observations of specific sites subject to major disturbances. A steerable lidar altimeter system, based on technological evolution of the VCL concept looks most promising for this mission, but SAR, multi-angle, and hyperspectral approaches also merit consideration. A complementary visible-infrared imager might be necessary to document the recovery of non-forest ecosystems. In addition, an ability to obtain hyperspatial data (~1m) is desired to enable characterization of fine-scale, sub-pixel spatial patterns and vegetation structure. It is envisioned that this exploratory mission could be implemented on a small spacecraft and aim for a 3-5 year life time to start during the 2007-2009 period, and that the hyperspatial data might be acquired through a data purchase. Despite the current high priority accorded carbon cycle science, this mission is proposed for selection and development only after the results of the VCL, Multi-angle Imaging Spectroradiometer (MISR), EO-1, SRTM, and other SAR (Japanese, Canadian, European) missions have been fully evaluated and the merits of their respective technologies assessed for this scientific application.

Atmospheric Carbon Dioxide Research Mission

Every region of the Earth's surface with a major carbon dioxide source or sink leaves a signature of excess or depleted carbon dioxide in the overlying troposphere. Available *in situ* measurements of near-surface atmospheric carbon dioxide concentrations have been used recently to constrain inverse models (see the section on inverse modeling in Chapter 7) of atmospheric transport and predict hemispherical scale distributions of carbon sources and sinks. However, deficiencies in the geographic coverage and spatial distribution of these observations severely limit the utility of the inverse modeling approach. An ability to make direct space-based measurements of atmospheric carbon dioxide concentrations, with sufficient accuracy and precision, would provide the needed global coverage and overcome problems with surface measurements within continents. Such observations would make it possible to identify, and at least roughly quantify, regional and sub-regional sources and sinks of carbon dioxide and to further constrain the location and/or identity of the missing global carbon sink(s). Advances in solid-state laser technologies suggest that it may be possible to make precise active remote sensing measurements of the total column and vertical profile abundance of carbon dioxide. Simulations also show that a high resolution spectrometer employing solar flux reflected from the ground could possibly provide precise measurements of total column carbon dioxide. Measurements of the carbon and oxygen isotopic composition of atmospheric carbon dioxide also might be possible. NASA is in the early stages of conducting an assessment of the potential for such space-based carbon dioxide measurements and is beginning to define the requirements for what could lead to a future mission focused on carbon cycle dynamics. This mission concept was first suggested after the post-2002 mission planning activity was completed and has yet to undergo a full science community review and priority assessment process.

Hyperspectral Observations and Data Analysis

Recent research with airborne hyperspectral sensors has demonstrated that very high spectral resolution (~10 nm) observations can be used to improve discrimination of vegetation types, phenological stage, canopy chemical composition, and physiological status well beyond what is now possible with multispectral instruments. Many of these applications require continuous spectra over some significant portion of the visible to short-wave infrared spectrum (0.4-2.5 µm). The NMP EO-1 technology demonstration mission will provide the first hyperspectral images from space. Terrestrial ecology and biogeochemistry research using EO-1 and other hyperspectral data (e.g. DOD Warfighter-1, NASA AVIRIS) will focus on advancing the applications for canopy chemistry and physiological status. Relationships between hyperspectral reflectance properties and canopy chlorophyll content, non-photosynthetic constituents, stress, and moisture status have been well-demonstrated. Correlation between canopy nitrogen and lignin content and hyperspectral reflectance continues to be seen, but not consistently, and the biophysical basis for the relationship remains elusive. Hyperspectral data have also shown promise for detecting and monitoring the spread of certain invasive plant species. NASA's plans for satellite hyperspectral data beyond the time frame of EO-1 depend very much on potential commercial and international initiatives and opportunities.

Cold Climate Land-Surface Process Research Mission

The Cold Climate Land-Surface Process research mission (see Land Surface Processes and Hydrology section, 4.3.3.1) addresses an ecosystem property of critical importance for refining estimates of the global carbon balance at high latitudes. Observation of freeze-thaw transitions in vegetation and soils would enable accurate estimates of the length of the growing season, which is the primary determinant of annual carbon uptake in high latitude terrestrial ecosystems. In particular, recent results from the U.S.-Canada Boreal Ecosystem-Atmosphere Study (BOREAS) have shown that the timing of springtime thaw can largely determine the annual uptake of carbon by boreal forests. The measurement concept for this mission is based on SAR imaging at moderate spatial resolution (~1 km) to detect freezing conditions at the surface. The primary payload would be a two-polarization, high accuracy SAR system at L-band or lower frequency. Moderate spatial resolution would allow complete coverage at high latitudes with a short repeat cycle (~3 days). NASA intends to investigate potential commercial and international initiatives in this domain.

Exploitation of New Satellite Observations

In the next few years, an unprecedented diversity of satellite data will become available for exploring new remote sensing applications in terrestrial ecology and biogeochemistry. The spectral resolution and dynamic range of MODIS will enable improved assessment of the occurrence, size, and temperature of fires. MISR will enable greatly improved estimates of surface albedo and analysis of vegetation canopy vertical structure. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) will provide the first multispectral thermal imagery at high spatial resolution. Global topographic data from the Shuttle Radar Topography Mission (SRTM) (see section 6.3.4 on Global Geology Studies) will be used as input to ecological models and to aid in satellite data corrections. Synthetic aperture radar (SAR) systems (see section 6.3.4) will allow further evaluation of disturbance, vegetation regrowth, and above-ground biomass; L-band or lower frequency sensors will be most useful. There is strong interest in continuing the scientific collaboration with Japan that was initiated to map forest cover and inundation under the JERS-1 Global Rain and Boreal Forest Mapping Project (GRBFM); Japan's Advanced Land Observing System's (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) to be launched in 2002 offers such an opportunity. There also is an emerging interest in exploring the application of geostationary satellite observations to studies of the diurnal cycle of fire activity. Research investments in each of these areas will not be large, but, rather, will be focused on evaluating the potential utility of the remote sensing techniques for specific ecological applications and identifying those most promising for future use.

Supporting Hydrological and Climatic Observations

Many scientific issues in terrestrial ecology and biogeochemistry can only be addressed when high-quality supporting hydrological and climatic satellite data sets are available. For example, systematic observations of surface temperature, humidity, and incident solar radiation are needed to drive ecological models, and information on clouds and atmospheric aerosols is needed to correct surface imagery. Such dependencies on observations obtained under other themes within the ESE must not be overlooked, and several post-2002 exploratory mission concepts offer exciting possibilities as well.

Soil moisture and rainfall are important climate-related controls on ecosystem productivity and carbon dynamics. The Soil Moisture research mission (see section 4.3.3) is of interest for characterizing near-surface soil moisture in sparsely vegetated ecosystems. If the measurement approach for this mission could be made more sensitive to soil moisture in regions of moderate to dense vegetation, and the spatial resolution increased, this mission would have even greater value. The Global Precipitation mission (see section 4.3.1) also is of interest if it can provide improved estimates of rainfall over land at ecologically-relevant spatial resolutions. Aerosol measurements (see section 3.3.1) are needed for improved atmospheric corrections and information on fire emissions. The Surface Water Level Monitoring mission (see section 4.3.3) is of interest for information on water flows from terrestrial to aquatic and marine ecosystems because of the implications of such water flows for biogeochemical cycling.

2.3.2.3 Field Campaigns and Process Studies for Terrestrial Ecology and Biogeochemistry

Major Field Campaigns

Field campaigns designed to address a specific global change science question and support comprehensive study of the relevant processes are a major element of ESE terrestrial ecology and biogeochemistry research. These campaigns typically involve coordinated *in situ*, airborne, and spaceborne observations of a particular site or region of the world, or along a gradient of environmental change.

The principal field campaign for 1999-2003 focuses on understanding the effects of tropical forest conversion to agricultural uses in Amazonia. This work is part of the Brazil-led Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). The topics addressed by NASA's ecological contribution to LBA (LBA-Ecology) include land cover and land use change (see LCLUC program element, section 2.3.3.2), carbon storage and exchanges, nutrient dynamics, and trace gas fluxes. Research on terrestrial carbon and nutrient dynamics involves quantification of the carbon and nutrient stocks in vegetation and soils of intact forests and savannas, pastures, cultivated lands, and second-growth and selectively-logged forests, as well as quantification of the rates of carbon and nutrient exchange among the atmosphere, vegetation, soils, and surface waters. This work will contribute to carbon cycle science by helping to reduce uncertainty in current estimates of the tropical deforestation carbon source, and also will help to quantify rates of carbon sequestration in re-growing, secondary forests. LBA-Ecology research on trace gas fluxes is focusing on quantification of the fluxes between the biosphere and the atmosphere and their controlling factors, with first priority accorded to nitrogen oxides and methane.

Local-scale measurements and process studies under LBA-Ecology will be conducted for a period of 3-5 years along gradients of land use intensity and seasonality of rainfall. The results will be used, in combination with regional-scale remotely sensed data and geographic information system (GIS) databases, to develop and validate models. A distributed data and information system (LBA-Ecology DIS) will enable data exchange among investigators and facilitate transfer to the public archives for LBA-Ecology at the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) and in Brazil. A partnership between LBA-Ecology DIS and a cluster of ESIPs has been formed to share data analysis tools and enhance tropical forest data availability and distribution. EOS instrument performance and data product evaluation will be conducted as part of LBA. LBA-Ecology research is closely coordinated with NASA's LBA-Hydrometeorology research (see section 4.3.3) and will benefit from the recent Tropical Rainfall Measuring Mission (TRMM-LBA) validation campaign in Brazil (see section 4.3.1).

NASA is making a substantial contribution to the Southern African Regional Science Initiative 2000 (SAFARI 2000) with cross-disciplinary sponsorship of several ESE program elements and led by the MODIS Science Team. The campaign aims to examine land-atmosphere interactions and characterize biogenic, pyrogenic and anthropogenic aerosol and trace gas sources and sinks in southern Africa. Results will be evaluated by comparing atmospheric transport and land-surface process model outputs with ground-based, airborne, and satellite-based observations. The campaign will take place across an environmental gradient from semi-arid grasslands to humid tropical woodland and covers a range of land use types. The field program includes satellite validation science focused on validating data products from the new instruments on the EOS Terra and Aqua platforms. The campaign will be conducted in 1999-2002.

Smaller-scale field campaigns focused on the evaluation of satellite sensor performance and validation of data products have been planned and can be expected to continue in association with the launch of new satellite missions. Validation of EOS data products will make use of a global network of test sites which includes long-term ecological research (LTER), Global Terrestrial Observing System (GTOS), and globally distributed flux tower (AmeriFlux and FluxNet) sites (NASA, 1999). Field campaigns to occur beyond 2003 will be planned in the near future.

Airborne Observations

Remote sensing and *in situ* observations from airborne platforms are key to the scaling strategy of major field campaigns; they provide the intermediate scale of observations bridging from the local-scale of field plots to the synoptic scale of satellite-sensed pixels. Airborne simulators or prototypes have been developed for many of the new satellite sensors and will be extensively used for validation in the upcoming years. Airborne sensors also provide unique data sets employing technologies not yet ready for or feasible from space that directly address priority science questions. Examples include the AVIRIS and the Advanced Solid-state Array Spectroradiometer (ASAS) that have been sources of hyperspectral and multi-angle data, respectively, for the past decade and, potentially, the airborne Lidar-Induced Fluorescence Transient sensor now being developed under the IIP to measure laser-induced fluorescence for estimation of photosynthetic efficiency in terrestrial vegetation.

In Situ Measurements

In situ observations are made and supporting data sets are assembled primarily (1) for systematic evaluation of satellite sensor performance and data product validation, (2) to provide customized input and test data for models, and (3) in support of specific field campaigns. NASA is currently supporting a number of carbon dioxide flux measurement towers (as a participant in the Department of Energy's AmeriFlux network and as a lead sponsor of the international FluxNet) to support validation of EOS NPP data products and NEP models and to study factors governing carbon fluxes from terrestrial ecosystems. This NASA investment in *in situ* observations is not intended to provide long-term monitoring.

Basic Remote Sensing Research

Basic research on the interaction of electromagnetic radiation with terrestrial ecosystems provides a theoretical basis for the utilization of remotely sensed data. Such research advances our ability to extract quantitative information from remotely sensed data. It also provides a theoretical foundation for developing new scientific applications of remotely sensed data and for identifying the signals of life that are of interest in Astrobiology for detecting life elsewhere. Future research will emphasize work that aids in the interpretation of data from upcoming satellite missions. Examples of priority research areas are: biophysics of laser profiling of vegetation canopies, cross-satellite calibration and atmospheric correction, intercomparison or fusion of data from complementary sensors (e.g., MODIS-AVHRR, Landsat-SAR), and inversion of simplified canopy models for biomass estimation.

Process Studies

Process studies to elucidate the physical, chemical, and biological controls on ecosystem responses to change are conducted principally in the framework of field campaigns. The terrestrial ecology and biogeochemistry program element conducts process studies to: (1) obtain information necessary for interpreting remotely sensed observations, (2) improve the formulation of key process mechanisms in ecological models, or (3) identify useful remote sensing surrogates for critical controlling factors. Future process studies will focus on obtaining the information needed to improve models of carbon dynamics. Other process studies will be conducted to advance our ability to incorporate into models the effects of multiple interacting stresses or to characterize and model trace gas dynamics. There is renewed interest in cross-disciplinary research focused on reducing uncertainties in our understanding of the global methane budget. Equally compelling, is a proposed cross-disciplinary effort on the role of fire in accounting for global trace gas and aerosol emissions to the atmosphere and in ecosystem nutrient cycling.

2.3.2.4 Modeling and Integration for Terrestrial Ecology and Biogeochemistry

The ability to understand and predict terrestrial ecosystem responses to environmental change, especially those responses that may take decades or even centuries to unfold, depends on our ability to model ecosystem functional and structural dynamics over a range of time scales. The objective is to develop realistic models that correctly portray key mechanisms and controlling factors and account for all important influences (e.g., multiple stresses, disturbance) on ecosystem function. The challenge is to make the models as simple and robust as possible without losing realism and useful predictive capacity. The modeling strategy requires a suite of ecological and biogeochemical models of varying complexity that operate over different spatial and temporal scales.

Modeling approaches to span spatial scales often nest fine-scale, process-level models hierarchically within one or more coarser-scale component models as a means of passing process understanding to regional scales and, ultimately, into global models. Remotely sensed data on land cover spatial pattern can be used to stratify a landscape so that process parameterizations or sub-models can be associated with cover types and then applied across the region being modeled. Presently, few of these nested modeling schemes are fully interactive, but that is a goal for the future. Lateral exchanges and storage of water, carbon, and nutrients are poorly represented in most current models, and this aspect of spatial modeling will be a focus for future improvement.

Research to couple models that capture processes operating at differing time scales (i.e., coupling physiological land surface to biogeochemical to successional to biogeographical models) is needed. Already the latest generation of terrestrial biosphere models incorporate a blend of such time varying ecosystem and land surface processes in a consistent framework. Further coupling and integration will be requisite steps toward eventual reciprocal coupling with other Earth system component models (e.g., GCM-type models). This will be absolutely essential for correctly portraying feedback loops – especially those that operate over long time scales (i.e., decades to centuries) and might not be captured in the short time scale models. NASA research will focus on developing and linking the models that take greatest advantage of remotely sensed data sets.

Predictions of future carbon cycle dynamics will require coupled biosphere-atmosphere-ocean models, and research toward this objective will be a priority. Progress has been made in the development of Dynamic Global Vegetation Models (DGVM) that are meant to interactively couple physiological models with climate models, and such research will be continued (IGBP, 1992; NRC, 1999). Strong collaborations across several ESE program elements as well as among many of the USGCRP agencies will be needed to further advance coupled Earth system modeling. NASA intends to be an active partner in this effort, focusing on model development and evaluation research that makes effective use of remote sensing and NASA field campaign data. Research toward other types of Earth system models will be approached in a similar, collaborative fashion.

Current ecological and biogeochemical models are most limited by the availability of high-quality data (especially long time series of data) for initialization or testing and by our understanding of critical controlling processes and interactions among them. Developing, improving, and managing needed input satellite data sets will, therefore, continue to be a priority. So will be the exploitation of new satellite observations (e.g., canopy height, vegetation structure, soil moisture). Process studies within field campaigns and model intercomparisons will be supported to advance our ability to identify and realistically model critical processes. For example, it will be important to better understand processes of carbon allocation, phenology, carbon turnover, disturbance, and succession, and to identify which are most critical to pursue. An ability to correctly portray disturbance has already been shown to be extremely critical.

Other modeling activities will focus on modifying or updating existing models to accept data from the new generation of satellite sensors, especially MODIS, Landsat 7, and VCL. The comprehensive data sets acquired in the BOREAS, LBA, and SAFARI 2000 field campaigns will be exploited for model testing and refinement. These and other data sets assembled and made available through the EOSDIS DAACs and ESIPs are critically needed for advancing global models. Opportunities will be sought within NASA's Astrobiology partnership to exercise Earth system biogeochemical cycling models to explore the co-evolution of life and the changing environment. Modeling is the key tool for synthesis and integration of scientific understanding, but not the only approach available. Analysis of empirical relationships within the framework of a GIS, direct analysis of remotely sensed time-series, and data assimilation also will be conducted.

2.3.3 LAND COVER AND LAND USE CHANGE (LCLUC)

The goal of the NASA land cover and land use change (LCLUC) program element is to develop the capability to perform repeated global inventories of land cover and land use from space and to develop the scientific understanding and models necessary to evaluate the consequences of observed and predicted changes.

This program element addresses land cover and land use changes and their causes and consequences (Questions V3, F2, C2, and C3). An important priority is to assess the impact of changes in land cover and land use on the global carbon cycle (Question C2). This program element recognizes that land cover and land use change can be responses to global environmental change and that they also act as forcings of global environmental change. Of primary interest are: the influence of human actions on land cover dynamics; associated impacts on the global carbon cycle, other biogeochemical cycles, and the global water cycle; and their implications for land management. There is also a desire to pursue fundamental investigations of sustainable land use and biodiversity.

Near-term research objectives for LCLUC research are to:

- document the spatial distribution and rates of change of land cover and land use;
- characterize changes in land cover and land use over the past several decades;
- examine biophysical and human forcings of change in land cover and use; and
- assess and predict the consequences of changes in land cover and land use.

The research approach requires:

- large-scale satellite data analysis and production of validated land cover data sets;
- regional case studies of specific biophysical processes and their social contexts;
- development of techniques for analyzing changes in land cover and use; and
- modeling of systems undergoing land use change.

The primary strategy is to balance the large-scale satellite data analysis with regional case studies that are designed to gain insight into specific biophysical processes and their social contexts. Priority will be given to areas of the world undergoing the most change and where stresses from human activities are likely to increase most rapidly. Key to this strategy are techniques in basic remote sensing and information science for advancing the analysis of changes in land cover and land use. Research to incorporate actual, observed land cover and land use into models is a near-term priority. Ultimately, the ability to model systems undergoing land use change will provide the relevant tool for both scientists and decision-makers to evaluate the consequences of different management practices and policies that affect land cover conversion. In the near-term, emphasis will be on understanding the role of land use change in carbon cycling in forested regions.

Spatial Distribution and Rates of Change

Emphasis is placed on the exploitation of satellite remote sensing data as the best source of information on the spatial distribution of land cover and rates of landscape change on regional, continental, and global scales. Time series of satellite data will be analyzed to (1) provide a consistent record of global land cover change, (2) characterize the end-states of land cover modification in regions of high population density, and (3) study the impacts of spatial patterns and past history of land use on ecosystem processes, biodiversity, and the sustainability of ecological services, such as recycling of nutrients.

Characterize Recent Changes

Improved recognition algorithms will be developed to address the current inadequacies of land cover classification and change detection techniques. Research will be conducted to use high resolution imaging radar data for characterizing basic land cover properties in areas of persistent cloud cover and to derive estimates of above-ground biomass and the extent of wetlands, the latter being directly related to methane and other trace gas emissions. Satellite data will be analyzed to understand long-term changes in the frequency of fire in forests and savannas. Data on land cover distribution and rate of change will be used in the analysis of the effect of spatial patterns and past history of land use conversion on ecosystem processes and structure. In this respect, the acquisition of global land cover data will support environmental assessments.

Biophysical and Human Forcings

The biophysical and human forcing factors that drive changes in land cover and land use are manifested through different phenomena such as fire, drought, flooding, insect infestations, disease, logging, and land clearing. Variability in weather, climate, and internal ecosystem dynamics drive land cover changes on decadal and multi-decadal time scales. Climatic and hydrologic variations and extremes can trigger persistent land cover changes that will, in turn, influence land-atmosphere exchanges for long periods of time. Successive years of drought or above average rainfall, for example, can change ecosystem composition, as well as land use practices or the frequency of fires. Population changes and economic activity are critical factors that determine the distribution and intensity of land cover modification and changes in land use. Pressures for economic development around the world and the demand for increased food production need to be expressed in quantitative terms and ultimately incorporated into models of land cover dynamics. Because ecosystems often respond slowly, understanding current land cover patterns requires taking into account land use history. ESE LCLUC research is linked to the wider effort to incorporate human dimensions into the study of environmental changes, and for the main part, NASA relies on the contributions of its national and international partners for the development of historical and socioeconomic data sets.

Consequences

Land cover conversion, land use intensification, and land degradation are consequences of particular importance for ESE research. Measuring the rates of rapid conversion of forest cover to other types, as is occurring in the humid tropics, and monitoring the fate of deforested land are of particular interest because of the linkages to the carbon cycle, trace gas emissions and tropospheric chemistry, hydrometeorology, biodiversity, and sustainable development. These data also will help in identifying land cover types that require further *in situ* studies in order to parameterize processes in landscape and ecosystem models. Other important research topics are the consequences of intensified management in agriculture, agroforestry, and grazing systems, the assessment of degradation processes in forests, and changes in land use across a region related to human population growth or migration (e.g., the loss of fertile farmland to urbanization).

2.3.3.1 Systematic Global Observations for Land Cover and Land Use Change

Systematic high-resolution satellite observations of the multispectral and multitemporal signatures of global land cover types are essential for study of changes in land cover and land use and their consequences on the storage of carbon, terrestrial productivity, biodiversity, runoff and soil erosion, and for a wide range of applications in agriculture, forestry, and range management. Thus, the foremost observational requirement for LCLUC research is to extend the more than 25-year record of Landsat-type observations, which constitutes the indispensable foundation for global land cover inventories. The Landsat 7 and EOS Terra missions will ensure the continuity and consistency of this essential environmental record for the next 5-7 years. The NMP EO-1 technology demonstration mission, intended to fly in formation with Landsat 7 and the EOS Terra spacecraft, will provide the first flight test of new imaging spectroradiometer designs that should enable future continued high-resolution mapping at much reduced cost. A series of Land Cover Inventory missions are planned for systematic observation of changes in global land cover and land use beyond 2005. Each would carry an instrument capable of producing multispectral imagery at high spatial resolution and obtaining global coverage seasonally (see Box 2 and TEB, section 2.3.2.1).

The principal approach for comprehensive analysis of seasonal, interannual, and decadal variability in the processes of land cover change will be systematic seasonal mapping of the entire global land surface using Landsat 7 and its successor high resolution imagers, ASTER, and/or radar data. Additional data from foreign and commercial satellites will be used when available. Global topographic data from SRTM (see Box 10 in Chapter 6: Solid Earth Science) will be used to refine land cover classifications.

Box 2
Land Cover Inventory Mission

The Land Cover Inventory mission series is intended to maintain the continuity of high-resolution land cover measurements. The required information is multispectral image data in the visible, near, and short-wave infrared ranges of the spectrum, with spatial resolution on the order of 10-30 m. Mid-morning overflight (equator crossing time) is desired. Orbital repeat time on the order of 2 weeks would provide acceptable sampling frequency, although more frequent observations would be desirable.

The New Millennium Program EO-1 mission will demonstrate a new lighter and more compact Landsat-class sensor design that may be applicable to the Land Cover Inventory mission. The sensor will provide similar or better spatial resolution and radiometric accuracy than the Landsat 7 Enhanced Thematic Mapper instrument, and appropriate spectral coverage for atmospheric corrections. The first Land Cover Inventory mission is tentatively planned for launch in the 2005 time frame, with a nominal mission life of 5 years. NASA intends to examine carefully private sector initiatives or potential data purchases as a means to acquire the desired high quality scientific information.

Past land cover and land use studies have been based predominately on AVHRR and Landsat data. A multi-scale approach to land cover characterization and monitoring is intrinsic to the strategy of the LCLUC program element. Many important and useful scientific results have been obtained (e.g. Landsat Pathfinder Humid Tropical Forest Project, Global 1-km Land Cover, and Fire Products) despite the lack of calibration and pointing uncertainties inherent to the AVHRR sensors. NASA has supported the acquisition of a global 1-km AVHRR data set that has proven to be an invaluable data resource for parameterization of land cover in climate and other Earth system component models and for global land cover classification. These early moderate-resolution products provide a context for time-series analysis of data from EOS instruments and their successors. The Global Land 1-km AVHRR Data Set was produced in cooperation with USGS, NOAA, the European Space Agency (ESA), and satellite ground receiving stations worldwide and in scientific dialogue with the International Geosphere-Biosphere Programme (IGBP). This partnership can be viewed as a model for the development of a cooperative strategy for systematic measurements, which must, to be successful, link research, long-term monitoring, and operational programs, including *in situ* observational networks, to provide effective monitoring of our planet on a global scale.

The Global Observation of Forest Cover (GOFC) Project now being implemented under the International Global Observing Strategy (IGOS) partnership follows in this tradition. The goal of GOFC is to develop operational forest monitoring systems to serve the needs of the global change science community, forest managers, and policy makers. This will involve combining satellite and *in situ* data and transitioning research methods and techniques into the operational domain. The NASA LCLUC program element is planning to make a significant contribution to GOFC within the overall international partnership.

EOS/MODIS and EOS/MISR instruments, successor moderate-resolution instruments planned for the Global Productivity Mission (See Box 1), and future operational NPOESS satellites will provide high quality moderate resolution land cover data for the long-term future. SeaWiFS, ESA's Along-Track Scanning Radiometer (ATSR) and the French Vegetation sensor offer complementary sources of 1 km land cover data, as will MERIS and AATSR on ESA's ENVISAT and GLI on Japan's ADEOS II in the near future.

2.3.3.2 Exploratory Satellite Observations for Land Cover and Land Use Change

Several of the exploratory satellite missions detailed in the section on Terrestrial Ecology and Biogeochemistry (2.3.2.2) also address observational needs for Land Cover and Land Use Change research. In addition to the EOS instruments mentioned above, the Vegetation Recovery Mission and hyperspectral observations have important land cover and land use change objectives. VCL is also of interest for measurements of ecosystem structure that can be used to improve land cover classifications. Additionally, the LCLUC program element has a need for hyperspatial data.

Hyperspatial Observations and Data Analysis

Remote sensing imagery with very high spatial resolution (~1 m) from aircraft, and more recently from unclassified national security systems, has proven to be extremely useful for analysis of the sub-pixel composition of imagery from coarser resolution sensors, determination of fine-scale spatial patterns, and inferring land use and management practices from both spatial and temporal patterns. Such hyperspatial imagery is now becoming available from commercial satellite operators (e.g., IKONOS), and purchase of such data for selected case study sites, or to sample sub-pixel variability in other types of studies, is a further option to meet this requirement for LCLUC research.

Vegetation Recovery Mission

The Vegetation Recovery Mission (see TEB, section 2.3.2.2) offers an excellent observational capability for studying responses of vegetation to changes in land cover and land use. It will be possible to quantify the recovery of most land cover types following major disturbances such as clear cutting and fires. In addition, the mission's scientific objectives could easily be expanded to include important scientific issues related to biogeochemical processes and landscape spatial patterns (e.g., habitat fragmentation and biodiversity) that are not directly related to the carbon cycle. The ability to acquire coincident hyperspatial data is an especially critical requirement for these scientific applications. Accurate co-registration of the hyperspatial and coarser resolution data from this mission will be essential for these LCLUC objectives.

Hyperspectral Observations and Data Analysis

The potential for using hyperspectral image data (see TEB, section 2.3.2.2) to improve discrimination of vegetation types and species composition and to enable the identification and mapping of more land cover types than is now possible using multispectral data is of enormous appeal. The NMP EO-1 technology demonstration mission will provide the first opportunity to evaluate such applications from space. Sources of hyperspectral data beyond EO-1 depend very much on potential commercial and international satellite initiatives and the continued availability of airborne hyperspectral imagers.

2.3.3.3 Field Campaigns and Process Studies for Land Cover and Land Use Change

Field experiments and process studies are employed to improve parameterizations in ecosystem models that simulate land cover change. Field campaigns to validate satellite data products also will continue to be an integral part of the program. Airborne remote sensing, primarily to acquire hyperspatial and hyperspectral data, will be conducted to aid in the interpretation of satellite data within these campaigns. For the next few years, LCLUC research conducted as part of the LBA-Ecology and SAFARI 2000 campaigns (see TEB, section 2.3.2.3) will emphasize linking the spatial and temporal dynamics of land cover change with analysis of the determinants of land use change in the context of regional case studies.

NASA will conduct process studies focused on the human dimensions of land cover and land use change when they can be related to observed, recent changes in the landscape. Case studies focused on understanding the economic, social, and policy factors responsible for forest conversion, land use intensification, and forest degradation will be focused on regions undergoing rapid change, including the U.S., Amazonia, Central America, Southeast Asia, Southern and Central Africa, and Russia. By choosing representative regions and typical changes in land cover and land use, it is hoped that the knowledge gained in these case studies will be applicable to other parts of the world.

The ESE LCLUC program element will continue to support essential *in situ* observations within its field campaigns, case studies, and satellite data analysis and validation research projects. For example, converting rates of land cover change into changes in carbon fluxes currently requires *in situ* measurements of biomass. Results from the Landsat Pathfinder Humid Tropical Forest Project suggest that while Landsat can detect the occurrence of intensive selective logging, *in situ* observations are required to arrive at consistent and reproducible regional estimates of slow degradation and to quantify biomass loss. Similarly, the calculation of emissions from biomass burning and determination of atmospheric impacts will require empirical emission factors that can only be derived from *in situ* observations.

2.3.3.4 Modeling and Integration for Land Cover and Land Use Change

Process studies and satellite observations are insufficient to arrive at the desired quantitative information on the causes and consequences of land cover change. Models are necessary to integrate fundamental knowledge of the operative processes and current observations, to investigate approaches for spatial and temporal scaling (from individual farms to regions), to simulate land use change responses, to assess consequences, and to predict future changes.

Because existing ecosystem models do not utilize data sets of actual land cover or land use, and are limited by this constraint, a core objective for LCLUC research is to develop methods to incorporate land cover and land use information into existing biogeochemical and biophysical models. This research will be conducted in close cooperation with model development activities in the national and international community. Model intercomparisons, such have been conducted under the joint NASA/NSF/USFS/Electrical Power Research Institute (EPRI) VEMAP study and in cooperation with the IGBP Global Analysis, Interpretation and Modeling (GAIM) core project, will be continued to assess improved models incorporating land cover and land use change information. In particular, the LCLUC program element will support the development of regional-scale integrated assessment models that can be applied to the evaluation of the potential outcomes of different management practices and assessment of the consequences of policies that affect land cover conversion.

Predictive models of the Earth System need to account for past and present extent and intensity of human land modification, and for the possible changes in these practices in the future. Predicting changes at the global scale will be challenging, since human decision making at the local scale is one of the most important drivers. Projections, therefore, will carry uncertainties of a different kind, as compared to physical or biological models, reflecting socioeconomic constraints as well as non-monetary influences on land use systems. Improved data sets of past and present land use are of highest priority for advancing current models. Modeling within the LCLUC program element will endeavor to cooperate with and build linkages to those programs that can add information, modeling tools, and realistic scenarios on social, economic, and policy influences on future Earth system change. The objective is to begin the research needed to develop coupled socioeconomic and natural science models for predicting scenarios of change in land cover and land use and their consequences.

The LCLUC program element also will invest in the development, refinement, and implementation of algorithms and data analysis methods to advance its objective of generating periodic global inventories of land cover and land use change. Synergies will be encouraged with EOSDIS, ESIPs, NewDISS, and other ESE programs that are also developing remote sensing data analysis and information processing techniques. Emphasis will be given to encouraging cost-effective and efficient data management, analysis, and archiving systems and to making the LCLUC data sets easily accessible and affordable for the research community.

2.4 LINKAGES

Linkages with other NASA programs

Scientific findings about primary productivity and ecosystem response to environmental change are the foundation for a broad range of potential applications in agriculture, forestry, fisheries, and environmental monitoring. Coordination with the ESE Applications programs will be emphasized to develop new applications of EOS, Landsat 7, VCL, and other new data types. Research on land cover and land use change in support of national and international environmental vulnerability assessments also will be a priority. The study of ecosystem disturbances by fire, flooding, oil spills, and extreme weather events provides the fundamental underpinning of applied studies conducted under the Natural Hazards program element. In particular, joint research on the impacts of fires will continue to be a priority.

Research on terrestrial ecosystem and land cover interactions with the atmosphere requires strong scientific linkages with the Global Water and Energy Cycle research theme, in particular the Land Surface Processes and Hydrology program element (section 4.3.3), recognizing that water is essential for all life and that vegetation controls fluxes of water into the atmosphere. Likewise, there are important linkages between river discharges and their chemical composition and coastal marine ecosystems. Equally strong linkages exist with the Atmospheric Chemistry, Aerosols and Solar Radiation research theme (see Chapter 3) as regards sources and sinks of trace gases and particulate matter (section 6.2.2). Likewise, the fundamental connection between ocean biological and biogeochemical processes and the ocean circulation is an essential linkage with physical oceanography (Global Ocean Circulation and Sea-Ice element of the Ocean and Ice research theme; section 5.3.1). These internal linkages are manifested by joint involvement in cross-disciplinary projects, including field campaigns.

The ESE's research on the biology and biogeochemistry of ecosystems contributes to NASA's cross-Enterprise research program in Astrobiology. In particular, ESE leads research efforts aimed at the Astrobiology goal of "determining how ecosystems respond to environmental change on time scales relevant to human life on Earth". ESE also contributes to Astrobiology through research on microbiology (related to controls on nutrient cycling and trace gas emissions), the development of Earth system models that simulate the co-evolution and adaptation of life and the changing environment, and on developing understanding of the "signals of life" that can be remotely sensed for Earth.

Linkages with other US agencies

ESE research on the biology and biogeochemistry of ecosystems and the global carbon cycle will be conducted as part of a larger national program coordinated by the Subcommittee on Global Change Research (USGCRP) of the Committee on Environment and Natural Resources (CENR). ESE also coordinates with the CENR Subcommittee on Ecological Systems. NASA recognizes the importance of the National and Regional Assessment Program of USGCRP and contributes scientific information based on satellite data products and regional land use change case and field studies. NASA has been a participant of the multi-agency Terrestrial Ecology and Global Change (TECO) Program with the National Science Foundation (NSF), the Departments of Energy and Agriculture (DOE; USDA), the National Oceanic and Atmospheric Administration (NOAA), and the Environmental Protection Agency (EPA). NASA has co-sponsored the VEMAP terrestrial ecosystem model intercomparison program along with NSF, the US Forest Service, and EPRI. NASA is a participant in the DOE-led AmeriFlux network of towers that measure carbon dioxide fluxes. The incipient National Oceanographic Partnership Program is expected to provide an effective conduit for NASA participation in a number of research programs that encompass the mission of several agencies, notably the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) and the Research and Monitoring Program on Ecological Effects of Environmental Stressors Using Coastal Intensive Sites (CISNet).

International linkages

Significant international cooperative activities are conducted in connection with major field campaigns. The LBA field campaign (section 2.3.2.3) is led by Brazil and involves substantial cooperation, both among individual scientists from the U.S., Brazil, other Amazonian countries, and Europe, and between NASA and the Brazilian Institute for Space Research (INPE). The BOREAS campaign and follow-on research have been conducted jointly with several institutions in Canada. The SAFARI 2000 campaign now being planned will involve the active participation of South Africa and other African nations. NASA also works with Russia on AVHRR data acquisition and the analysis of the effects of fires and other disturbances on boreal forest productivity and carbon dynamics. The validation of EOS data products requires a worldwide network of test sites where *in situ* observations are made. NASA contributed to the selection of the sites, and has exercised leadership in coordinating a network of international carbon flux tower networks (FluxNet) and in organizing data and information exchanges.

Intercomparison and exploitation of satellite data sets constitute another focus for international cooperative activities. NASA is a sponsor of the International Ocean Color Coordinating Group (IOCCG), an affiliate organization of the international Scientific Committee on Oceanic Research, that provides a forum for the exchange of information and technical guidance on ocean color measurements between space agencies with current or planned ocean color satellite missions. As part of the SIMBIOS program, NASA co-sponsors validation cruises with other countries. In addition, NASA maintains or supports ocean moorings that provide basic optical validation data for all ocean color measurements. NASA is planning a significant contribution to the Global Observation of Forest Cover Project (under the International Global Observing Strategy (IGOS) Partnership and the Committee on Earth Observation Satellites (CEOS)). The goal of this project is to develop operational forest cover monitoring systems to serve the needs of the global change science community, forest managers, and policy makers. NASA is also a partner in the Global Rain and Boreal Forest Mapping Project led by Japan, based on the use of JERS-1 SAR data to map inundated wetlands in Amazonia and to classify tropical and boreal forest ecosystems globally.

The research agenda for NASA research on the biology and biogeochemistry of ecosystems and the global carbon cycle is heavily influenced by the scientific plans and initiatives of the International Geosphere-Biosphere Programme (IGBP) of the International Council of Scientific Unions. In particular, NASA supports the Global Change and Terrestrial Ecosystems (GCTE) Focus 1 project office and has developed regional land cover and land use science networks in Southeast Asia and Southern Africa (in partnership with the System for Analysis, Research, and Training in global change science (START) initiative of IGBP). Various land cover and land use research activities are implemented in conjunction with other international programs such as the U.S. AID Central Africa Project for the Environment (CARPE) and relevant host countries.

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CHAPTER 3

ATMOSPHERIC CHEMISTRY, AEROSOLS AND SOLAR RADIATION

3.0 INTRODUCTION

The Earth atmosphere is the fluid that most directly connects the other components of the Earth System (the oceans, marine and terrestrial ecosystems, geosphere and cryosphere) and provides the medium in which these components interact. It is a chemically complex and dynamic mixture whose composition and structure are determined by competing processes. Changes in that balance, caused by natural phenomena or human action, can strongly influence life on Earth, either directly through change in atmospheric composition, or indirectly through chemical impacts on climate and the biosphere. Atmospheric change is the result of strongly interactive chemical and physical processes. Atmospheric radiation transfer and temperature depends on chemical composition and the distribution of atmospheric aerosols, while the nature and rates of chemical processes depend on temperature. As a result, chemistry plays a crucial role in determining the Earth climate, while the physics and dynamics of the atmosphere influence chemical processes and composition.

The goals are to measure and understand how and why the global atmospheric composition, aerosol distribution and properties, and solar radiation are changing in response to natural and anthropogenic forcings, and to enable accurate prediction of future changes in climate, ozone distribution, surface ultraviolet radiation, and global pollution.

3.1 MAIN SCIENCE QUESTIONS

- ***How is stratospheric ozone changing as the abundance of ozone-destroying chemicals decreases?***

It has been established that the primary cause of the stratospheric ozone depletion observed over the last two decades is an increase in the concentrations of chlorofluorocarbons (CFCs) and other halogen-containing hydrocarbons of industrial origin. The depletion has been significant, ranging from a few percent per decade at mid-latitudes to greater than fifty percent seasonal losses at high latitudes, notably the annually recurring Antarctic ozone hole, as well as smaller but still large, winter/spring ozone losses observed recently in the Arctic. Reduction in atmospheric ozone amounts leads to increased flux of ultraviolet radiation at the surface, with harmful effects on plant and animal life, including human health.

In response to these findings, the nations of the world have ratified the *Montreal Protocol on Substances That Deplete the Ozone Layer* and agreed to phase out the production of several halogen-containing chemicals. Concentrations of many such compounds are now beginning to decrease in the lower atmosphere, and there is some evidence that ozone-depleting substances are approaching their anticipated peak levels in the stratosphere. All other things being equal, as the halogen burden falls in response to regulation, stratospheric ozone concentration should begin to recover. However, the future behavior of ozone will also be affected by the changing abundance of water vapor, methane, nitrous oxide, sulfate aerosols and changing temperature. Thus, for a given atmospheric halogen burden, stratospheric ozone amounts will not be the same in the future as it was in the past.

One of the principal challenges to atmospheric chemistry research in the coming decade are to identify the signs of ozone recovery and to verify that CFC substitutes and other industrially produced halogenated compounds are indeed decreasing as expected from the application of the Montreal Protocol. In addition to climate change, transient phenomena like volcanic eruptions and particle precipitation events, variations in solar irradiance and atmospheric circulation also affect stratospheric temperature, water vapor and aerosols and, in turn, influence stratospheric ozone. Systematic observation is crucial to understand the origins of observed ozone changes and their causes, natural or human. NASA's ozone observation and upper atmosphere research plans are consistent with the responsibility defined by federal legislation (NASA Authorization Act and the US Clean Air Act).

- ***What trends in atmospheric constituents and solar radiation are driving global climate?***

The increasing concentrations of long-lived trace constituents that absorb infrared radiation, such as carbon dioxide, nitrous oxide and methane, are primary forcing factors of global climate change. The growth rates of these constituents in the atmosphere show considerable variations, that are currently not well understood. Quantifying the sources and sinks of these constituents is the basic issue for establishing future greenhouse gas concentration scenarios. Transient variations and changes in the concentrations of shorter-lived greenhouse gases involve a more complex combination of dynamical, physical, and chemical processes. Ozone depletion in the lower stratosphere introduces a cooling tendency, while the increase in tropospheric ozone introduces a warming tendency. Water vapor in the upper troposphere and lower stratosphere likewise has a powerful greenhouse effect.

Stratospheric aerosols, such as that result from large volcanic eruptions (most recently Mt. Pinatubo in 1991) can significantly cool the Earth's climate, as has been demonstrated by several recent events. Tropospheric aerosols, on the other hand, can either cool or warm the atmosphere, depending upon their properties and the albedo of the underlying surface. Tropospheric aerosols also influence climate indirectly by modifying cloud microphysical properties and lifetime. The details of aerosol impacts on atmospheric radiation strongly depend on the nature of the aerosols. Thus, a major scientific challenge is understanding the processes that lead to aerosol formation, and the diversity of aerosol types and chemical compositions.

Solar radiation is the only climate forcing factor that is truly external to the Earth system. We know that the Sun's radiant energy output has increased materially since the distant past, apparently without any drastic change in Earth's climate – thus pointing to the existence of stabilizing feedback mechanisms operating over very long time scales. Over shorter time periods, however, any change in solar activity and radiation will affect the Earth's radiation budget and climate. Furthermore, solar radiation is considerably more variable in the ultraviolet part of the spectrum than at longer wavelengths (5% over a solar cycle in the spectral range involved in stratospheric ozone production). The extent to which resulting variations in stratospheric composition and thermal structure influence climate in the lower atmosphere remains to be quantified. Monitoring solar radiation (both total and spectrally resolved) is indispensable to account for solar-induced variations in atmospheric climate and chemistry.

- *How* ***do stratospheric trace constituents respond to climate change and chemical agents***

Changes in physical climate affect the distributions of trace constituents (e. g. ozone), and vice versa. As the already depleted ozone layer enters the period of its greatest vulnerability, recently detected stratospheric cooling – a predicted side effect of both ozone depletion and increased concentrations of other greenhouse gases – may delay the recovery of the ozone layer and enhance its susceptibility to natural or human-induced perturbations. For six out of the last nine years, unusually low late-winter to early-spring ozone concentrations have been observed in the Arctic stratosphere, in conjunction with unusually cold and protracted stratospheric winters. In addition to these polar effects, increasing abundance of greenhouse gases can also affect the climate, chemistry and ozone content of the middle latitude stratosphere.

Chemical reactions that occur on the surface of stratospheric aerosol and/or cloud particles are temperature dependent; even a small decrease in temperature could cause a significant increase in the rates of these reactions. Changes in stratospheric water vapor, associated with changes in fluxes through the tropopause, could enhance the formation of aerosol and cloud particles that facilitate ozone destruction. Furthermore, a decrease in ozone amount would result in a reduction of solar UV absorption, further cooling, further enhancing ozone loss (a positive feedback). There is already strong evidence of cooling temperatures in the lower stratosphere, one of the largest climate signals measured in the atmosphere over the past 20 years.

Hydroxyl radicals (OH) formed largely from ozone and water vapor are the principal oxidizing agents in the atmosphere. Any changes in hydroxyl amounts, especially in the troposphere, will affect the lifetime and distribution of many trace constituents, including ozone, chlorofluorocarbon replacements, and even slower-reacting species like methane. Changes in hydroxyl will also affect the formation of aerosol. In addition to its direct impact on climate, the troposphere is the ultimate source and sink for stratospheric trace constituents; tropospheric interactions between meteorological, physical and chemical processes are still far from being adequately understood. The spatial and temporal variability of both long-lived and short-lived chemical constituents is a major impediment to scientific knowledge of global effects, such as radiative forcing of climate and long-range dispersion of pollutants.

Improving our understanding of this highly interactive system calls for detailed investigation of the relationships between the distributions of ozone, water vapor, aerosols, temperature, and relevant trace constituents, notably chlorine and bromine compounds and nitrogen oxides. In view of the high spatial variability of these constituents, good horizontal and vertical resolution will be needed, especially in the vicinity of the tropopause (upper troposphere and lower stratosphere).

- ***What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?***

With the growth of population, economic activity and use of fossil fuels, particularly in Asia and Latin America, emissions of pollutant gases such as carbon monoxide, sulfur dioxide, and oxides of nitrogen will undoubtedly increase. There is now significant evidence that such gases can be transported over very large distances (e.g., across the Pacific or Atlantic oceans). Aerosol from biomass burning and effluents from fossil fuel combustion have been readily detected in the lower troposphere thousands of miles from their sources. The global effects of atmospheric pollution are poorly known because natural emissions of trace constituents, removal by wet and dry deposition and chemical reactions in the atmosphere or at the Earth's surface are not well characterized globally.

The combined effect of increased pollutant levels and changing temperatures, winds, and precipitation patterns must also be considered. Unlike the relatively calm stratospheric environment, the troposphere is a very active medium. Convection is a major element of complexity, effectively coupling the upper and lower troposphere. In particular, large scale atmospheric motions move pollutants around in ways that are greatly complicated by the significant geographical and seasonal variations in convection, which in turn plays a key role in establishing the vertical mixing of pollutants and, ultimately, their global distribution. Other complicating factors are the condensation, re-evaporation or precipitation of water, which affects the concentrations of soluble trace gases and aerosols, and lightning, which acts as a strong source of reactive constituents where it occurs. Aircraft traffic that results in the emission of ozone and aerosol precursors, and other effluents directly in the upper troposphere and stratosphere may also be a factor. Further advances in the knowledge of tropospheric chemistry will require integrating chemical and meteorological knowledge in comprehensive interdisciplinary studies.

Anthropogenic emissions transported on a global scale enhance the background concentrations of pollutants in populated regions far downwind from their source, increasing the severity and scale of pollution episodes in these regions. For example, it has been suggested that rising Asian emissions could adversely affect ozone air quality in the western U.S. It has also been suggested that long-range transport of African dust could contribute to degradation of visibility in the southeastern U.S. As air quality standards become more stringent to respond to increasing public expectations the influence of rising background concentrations becomes an increasingly important issue. Changes in atmospheric stability and circulation due to regional pollution is another mechanism by which perturbations in atmospheric composition could induce changes in regional air quality.

Understanding and predicting tropospheric transport, physics and chemistry will be a frontier area of atmospheric research for the next decade and probably beyond. Tropospheric chemistry poses an interdisciplinary challenge for the Earth science community. These are global scale problems that are particularly well suited to the use of space observations and correlative *in situ* measurements. Knowledge of these phenomena is needed to evaluate the effects of chemical changes on the global hydrological cycle, the cycling of nutrient compounds through the earth environment, the accumulation of greenhouse gases, the acidity of rain and snow, and the formation of ozone in the lower troposphere.

3.2 SCOPE AND NATURE OF THE PROBLEM

The main science questions map onto scientific problems that go well beyond the traditional discipline of atmospheric chemistry. Close collaboration between atmospheric chemists, radiation science specialists, meteorologists, and interdisciplinary scientists interested in biogeochemical cycles will be needed to successfully address these issues.

Stratospheric Ozone

How is the global distribution of ozone changing and how will it evolve in the future, given likely changes in both industrial activities and the underlying climate? Changes in the amount of ozone in the Earth's atmosphere that occurred over the last few decades are well documented by both ground- and space-based measurements. Statistically significant decreases in total column ozone amounts have been observed over most of the globe (with exception of the tropics), including depletion rates on the order of several percent per decade at mid-latitudes. Considerably larger losses have been observed at high latitudes, especially in the Antarctic spring where major ozone depletion (the "ozone hole") occurs systematically every year. The ozone loss corresponds to more than 50% of the original total column amount during Austral spring and temporarily reaches almost 100% at some lower stratospheric altitudes. In the Arctic, no such systematic ozone loss has taken place, but large decreases in total column amount have been observed in late winter and early spring, reaching 50% during one particular winter (1996-97).

Ground-, aircraft-, and space-based observations have shown that chemical reactions involving industrial halogen products, whose concentrations are affected by chemical reactions occurring at the surface of aerosol and cloud particles, are primarily responsible for ozone depletion in the lower stratosphere. The concentration of chlorine in the stratosphere, now above 3.5 parts per billion by volume, dramatically exceeds the level (~0.6 parts per billion) that would exist in the pristine stratosphere unaffected by industrial activity. Bromine is also found in the stratosphere at levels much greater than would occur in the absence of industrial activity. Chemical reactions occurring at the surface of aerosol and cloud particles are a necessary intermediate step to explain the magnitude of both polar ozone depletion (polar stratospheric clouds) and mid-latitude depletion in the lower stratosphere (sulfate aerosols). The amount of sulfate aerosols present can be greatly enhanced by oxidation of sulfur dioxide injected directly into the stratosphere by large volcanic eruptions. The conversion of SO_2 to H_2SO_4 takes place with a time constant of a month, with subsequent decay of the resulting aerosol over a period of 3-5 years. The large reduction in global ozone amount that occurred subsequently to the eruption of Mt. Pinatubo in June, 1991 was definitely shown to result from such aerosol-induced chemical reactions.

Global measurement by surface-based networks have shown that the implementation of the Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments has achieved a significant reduction in the atmospheric concentrations of several chlorine-containing compounds (carbon tetrachloride, methyl chloroform). Growth in other source gases, such as trichlorofluoromethane (CFC 11), has essentially ceased. Satellite, balloon, and aircraft measurements have shown evidence of slower growth of chlorine levels in the stratosphere. As emission controls become more effective, stratospheric chlorine levels are expected to begin declining during the next decade. On the other hand, bromine-containing halons, also regulated under the Montreal Protocol, continue to increase at rates which exceed predictions and could delay the expected recovery of stratospheric ozone if the current trends continue into the next decade.

The sources and sinks of halogenated hydrocarbons, such as the hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), which serve as replacements for the banned chlorofluorocarbons (CFCs), are not well understood. The concentrations of HCFCs and HFCs are now growing rapidly in the atmosphere, This lack of understanding is especially evident for methyl bromide, which has both industrial sources and natural sources and sinks at the land surface and in the ocean. Methyl bromide is the primary source of bromine that can reach the Earth's stratosphere. Significant uncertainties exist in the global budget of methyl bromide and the strength of surface sources, even to the point where it is not known which regions are sources or sinks. This issue is complicated by the fact that the cycling of methyl bromide between the surface and the atmosphere may be quite rapid, and the net accumulation is a relatively small residual between larger production and removal terms. There is also increasing interest in understanding the sources of naturally-occurring chlorinated hydrocarbons, about which little is known, as well as the role of the oceans as a sink for chlorinated hydrocarbons, such as methyl chloroform and carbon tetrachloride. These unresolved questions highlight the need for improved understanding and continued monitoring of surface concentrations of the full range of industrially produced halocarbons.

Ozone recovery can be affected by climate-related changes. Stratospheric cooling, increase in the concentrations of stratospheric water vapor or other chemically-active molecules, and change in circulation patterns that affect stratosphere-troposphere exchanges or the stability and temperature of winter polar vortices, could all have significant impacts on future ozone levels. It is conceivable that climate change might be at least partly responsible for large Arctic ozone losses observed in recent winters. These findings indicate that verifying the recovery of stratospheric ozone will be complicated by the large interannual variability in the stratospheric circulation, which needs to be documented as well. In addition, the mechanisms coupling climate change, the flow of wave energy between the troposphere and the stratosphere, and the stability of the polar vortices need to be understood. Finally. the timing of ozone recovery will also be affected by changes in the amount and distribution of stratospheric aerosols (see below).

Aerosol Chemistry, Sources and Sinks

The role of aerosols in the global environment has received increased attention in recent years, notably because the global-mean radiative forcing associated with anthropogenic aerosols could be on the same order of magnitude (but with the opposite sign) as greenhouse gas forcing (IPCC, 1995). In addition, aerosols play an important catalytic role in atmospheric chemistry (notably ozone-destroying reactions) and contribute significantly to surface deposition of nutrients as well as particulate matter that may be harmful to human health. In particular, terrestrial and marine aerosol transported over long distances from their sources can provide critical nutrient subsidies, such as iodine transported by salt aerosols into the interior of continents or iron from mineral dust deposited in the oceans. The ocean ecosystem is critically dependent upon such iron inputs to sustain nitrogen fixation and photosynthesis by phytoplankton. As the mobilization of iron-rich mineral dust from desert regions is related to winds and aridity, a feedback process exists between the hydrological cycle and the rate of absorption of atmospheric CO_2 mediated by biological processes in the ocean.

The complexity of aerosol physics and chemistry, their space and time variability, and the diversity of aerosol compositions and particle sizes, add up to a daunting challenge for both experimental research and modeling. The primary cause of the extreme diversity of aerosol types and properties is the multiplicity of aerosol sources: sea spray, smoke from fires, volcanic ash and mineral dust from deserts and arid regions, smoke from fires, and atmospheric formation of sulfate particles from the oxidation of sulfur-containing compounds from natural or industrial sources. Biological production of dimethyl-sulfide (DMS), dimethyl-sulfonium propionate (DMSP) and, ultimately, sulfur-based aerosols by oceanic phytoplankton may constitute an important feedback mechanism between oceanic biological productivity and climate. Volcanic eruptions can inject enormous amounts of ash and SO_2 in the troposphere and stratosphere. The lofting of mineral dust under dry and windy meteorological conditions is partly controlled by human-induced changes in land use and agricultural practices. Biomass burning, particularly in the tropics, is a major source of tropospheric aerosol, and an important contributor to global budgets of radiatively and chemically active trace gases.

Stratospheric aerosols, linked to volcanic eruptions, are at their lowest level since the inception of global aerosol measurements some 20 years ago. Observations of these low values, coupled with better information on the concentrations of aerosol precursors and knowledge of aerosol microphysics, have called into question established ideas about the origins of background aerosols. The contribution of aviation to stratospheric aerosol loading is an open question. Quantifying the processes that govern the stratospheric aerosol background will be an important scientific goal, should injection by volcanic eruption remain small.

Atmospheric Processing and Removal of Trace Constituents and Aerosols

The global burden of atmospheric methane has more than doubled since pre-industrial times, accounting for about 20% of the estimated climate forcing by anthropogenic greenhouse gas emissions. Yet analysis of measurements for the period 1984-1996 reveals that the methane growth rate has varied considerably and recently slowed down; the origin of these variations is not understood. The cause of this decline in methane growth rate could be due to an increase in the atmospheric sink resulting from the increase in the concentration of tropospheric OH, although a decrease in methane emissions cannot be ruled out. If the current trend persists, the methane concentration in the atmosphere could stabilize at a level only 5% above those existing today. This new finding underscores the importance of acquiring consistent global methane concentration records, as well as improved understanding of the processes that control methane distribution. These include methane emission from both natural and anthropogenic sources and methane destruction dominated by reaction with the hydroxyl radical, the concentration of which may also be changing.

The observed increase in upper stratospheric water vapor goes well beyond that which could result from an increase in production from the oxidation of methane, suggesting larger water transport from the troposphere to the stratosphere. Such an increase could result from a relatively small warming of tropopause temperature (not substantiated by observation yet). Another difficulty in ascertaining trends in stratospheric water vapor is the high degree of variability observed in upper tropospheric water vapor. Better measurements of upper tropospheric water vapor and temperature will improve our understanding of this important global change parameter.

Global satellite observation have led to rapid advances in knowledge of the distribution of tropospheric aerosols, especially those resulting from long-range transport of mineral desert dust, smoke from biomass burning, sulfate aerosols, and volcanic ash. *In situ* measurements have shown the composition of tropospheric aerosols to be considerably more complex than previously thought, including the presence of large amounts of organic compounds in some cases. Once airborne, the fate of aerosol particles can vary enormously. In some regions, aerosol particles serve as cloud condensation nuclei and are thus removed from the atmosphere. At other locations, aerosols can be transported over long distances, e.g. the observed transatlantic transport of mineral dust from the Sahara desert or the near complete circuit of the Earth made in the mid-troposphere by aerosol particles originating from biomass burning. Hygroscopic aerosols are particularly susceptible to transformation in the moist troposphere; their particle size distributions "age" as a result of such transformation, with corresponding changes in sedimentation rate and optical properties. In the stratosphere, aerosol particles formed by oxidation of sulfur dioxide have an e-folding time of nearly a year and disperse over the whole Earth; their global distribution is a sensitive indicator of the effectiveness of large-scale atmospheric transport and mixing. In view of the complexity of the dynamical, physical and chemical processes involved, developing reliable representation of aerosols in atmospheric models is a daunting scientific challenge.

Solar Radiation Forcing of Atmospheric Chemistry and Climate

The Sun is a mildly variable star that exhibits cyclical variations in its internal activity and radiation output. The primary external forcing of the Earth climate is produced by variations in the Sun's total energy output, which are currently too small (less than 0.2% over an 11 year solar cycle) to induce significant changes in the lower atmosphere. The much larger variability in solar ultraviolet radiation does affect the chemistry and composition of the stratosphere and upper atmosphere. Variations are a few percent in the ultraviolet spectrum range involved in stratospheric ozone production, but as large as a factor 2 at the shorter wavelengths that affect photochemistry in the upper atmosphere (above the stratosphere). Changes induced by solar variability in the stratosphere could potentially affect the tropospheric general circulation and climate. Neither the mechanisms nor the extent of these interactions are definitely known at present.

Chemistry-Climate Connection

Climate change can affect atmospheric chemistry in several ways. Temperature affects reaction rates and the natural emission rates of source gases. Changes in atmospheric circulation can modify the transport of radiatively and chemically active trace constituents within the troposphere and stratosphere, as well as across the tropopause. Weather phenomena determine the location and duration of persistent meteorological conditions that enhance air pollution or cause its removal from the atmosphere. Aerosol formation and microphysics are affected by atmospheric temperature and moisture. Conversely, ozone, other chemically active trace constituents, and aerosols contribute significantly to the atmospheric greenhouse effect and can induce changes in the atmospheric circulation and climate. Understanding the linkages between atmospheric chemistry and climate change is a major multi-disciplinary challenge for Earth system science.

On the other hand, half the total increase in global greenhouse effect since the beginning of the industrial era is due to the combined radiative effect trace constituents other than CO_2. On a per molecule basis, compounds such as methane, nitrous oxide, chlorofluorocarbons, and ozone are significantly more effective greenhouse gases than CO_2. One explanation of the apparent discrepancy between climate model simulations and the global warming trend observed over the last 30-40 years is an underestimation of the (negative) radiative forcing due to anthropogenic aerosols. Knowledge of the time-dependent 3-dimensional distribution of aerosol will be needed in order to discriminate between natural and anthropogenic sources. The same information is also needed to exploit opportunities for natural "climate forcing experiments" offered by volcanic eruptions that inject large amounts of sulfur dioxide into the stratosphere and can enhance the stratospheric aerosol loading for periods of several years.

The optical properties of aerosol are complex functions of number density, particle size distribution, particle shape, and chemical composition of the material. The direct radiative forcing caused by aerosols depends upon all these properties and also, most importantly, upon masking by clouds and the underlying surface albedo. In addition, indirect radiative forcing can be induced by certain classes of aerosol acting as cloud condensation nuclei (See section 4.3.2 in the next chapter).

Global Pollution

There is growing evidence that increasing regional air pollution contributes significantly to planetary scale changes in atmospheric trace constituents, including precursors for ozone formation, other oxidants, and particulate matter. The development of Asian economies and the growing use of fossil fuels will lead to significant increases in air pollution in East Asia and to degradation of air quality in currently clean air regions of the Pacific Basin. A significantly increased pollution plume from Asia could potentially affect air quality on the West Coast of the United States. This is just one example of cross-boundary pollution issues that will assume increasing importance in the next few decades. Large plumes of pollutants are transported to the free troposphere through convection and travel great distances downwind of their sources. Observations made over the tropical Pacific Ocean and off the west coast of North America show clear evidence of such transport into regions that would otherwise be free of pollutants. Effluents from African and South American biomass burning has been observed over the tropical Atlantic. African and South American plumes are seen over the central and Eastern South Pacific Ocean. Mineral dust from the Saharan desert crosses the Atlantic Ocean all the way to the Caribbean Sea and, in some instances, the southeastern US. The consequences of long-range transport of atmospheric pollutants need to be quantified so that non-local influences can be factored into local changes in atmospheric chemistry and pollution.

3.3 NASA Program Elements

The NASA research strategy in atmospheric chemistry involves four categories of activities: process studies, systematic observation of the distribution of relevant quantities, model simulations and retrospective analysis of past observation records, and model predictions of future atmospheric changes. Scientific breakthroughs in understanding the complex problems described in the previous section come from the synergy of these four research elements.

Process-level understanding is needed to form an accurate conceptual picture of how chemical constituents and aerosol particles form, interact, and are transported in the atmosphere. Laboratory experiments provide much of the detailed information on gas-phase reactions of trace constituents, the formation of aerosol particles from chemical precursors, fundamental chemical and physical properties of aerosol particles, and chemical reactions that occur at the surface of aerosol and cloud particles. Theoretical knowledge can also be applied to understand aerosol particle formation and growth. Information on transport processes comes from the interpretation of detailed atmospheric constituent distribution data, as well as knowledge of the atmospheric circulation.

Ground-, aircraft-, balloon-, and space-based measurements are used to determine the concentration of chemical constituents, the distribution and properties of aerosol particles, transport between different regions of the atmosphere, and atmospheric temperature and wind fields. Parameters that affect atmospheric processes, such as solar ultraviolet radiation and energetic particle fluxes, also need to be documented. Observations range over all spatial and temporal scales, from short-term, focused studies of a particular region of the atmosphere, to systematic global measurement by satellites and surface-based networks.

Detailed comparison of observations with the results of model simulations test both our understanding of processes as they occur in the atmosphere and our understanding of the past evolution of atmospheric composition in relation to changes in halogen abundance, variations in solar radiation, and effects of volcanic eruptions. Models range in complexity from relatively simple photochemical box models, that represent chemistry within each atmospheric volume assuming no atmospheric transport, to fully interactive 3-dimensional models that can simulate chemical, radiative, and transport processes.

Predictions of the future changes in atmospheric composition and physical properties usually require fully interactive multi-dimensional models representing atmospheric chemistry and transport. Much of this activity has been applied to international assessments, especially the Scientific Assessment of Ozone Depletion: 1998, by the World Meteorological Organization and the United Nations Environment Programme (WMO, 1998). Such models have been used, for example, to predict the response of the atmosphere to the different halogen loading scenarios that could result from the Montreal Protocol (e.g. speeded up phase-out of some compounds). Important assessment activity has also been carried out to support the NASA Office of Aero-Space Technology to estimate the atmospheric effects of aviation. Even more ambitious model developments attempt to simulate detailed interactions and feedback between meteorological, chemical, and radiative processes, such as gas and mixed phase chemical processes in the troposphere.

Particulate matter is another type of trace constituent with unique physical and chemical properties. A comprehensive aerosol research program must consider processes that cut across all disciplines of Earth system science, including: (i) aerosol production, transport, and scavenging (ii) impacts on radiation transfer, (iii) impacts on chemical reactions and, (iv) nucleation processes. Advances in global aerosol science so far have been based mainly on inferences from model simulations built on much theoretical knowledge and limited observational data. The strategy is to reverse this trend and:

- Augment systematic aerosol measurements that can be applied to test global aerosol models (AERONET, first EOS mission series).

- Develop *in situ* airborne measurement campaigns and global observation (PICASSO-CENA research satellite mission) to investigate aerosol properties and processes.

3.3.1 GLOBAL SYSTEMATIC MEASUREMENTS

Currently, the NASA global atmospheric chemistry research program is principally organized around a major global monitoring and discovery mission EOS Aura (2002-2007) as part of the Earth Observing System (EOS) program. EOS Aura will build on the heritage of measurements initiated by the still active UARS spacecraft launched in 1991. Instruments on the EOS Aura mission that are focused on stratospheric chemistry include:

- The High Resolution Dynamics Limb Sounder (HIRDLS) instrument, using infrared emission to measure ozone, water vapor, temperature, and a broad range of trace constituents, including long-lived source gases and most of the important nitrogen-containing species (N_2O, NO_2, HNO_3, N_2O_5, $ClONO_2$) in the upper troposphere and stratosphere. The high vertical and horizontal resolution of HIRDLS measurements will make a unique contribution to knowledge of stratospheric constituents and the transport of trace gases between different regions of the stratosphere and troposphere. HIRDLS is a joint development of the US and United Kingdom.
- The Microwave Limb Sounder (MLS) using emission in the microwave spectrum to observe the distribution of ozone, water vapor, long-lived tracers like N_2O, halogen compounds and, for the first time, the OH, HO_2, and BrO radicals. Simultaneous measurements of ClO and HCl will also made for the first time from space. These observations will allow a critical test of current understanding of the partitioning of chlorine between possible reservoir species. MLS measurements will thus enable the first ever global characterization of catalytic ozone destruction rates through measurements of radicals in all key chemical families (HO_x, NO_x, ClO_x, and BrO_x).
- The Ozone Monitoring Instrument (OMI), supplied by the Netherlands, will measure total column amounts of ozone. The OMI total column ozone data will extend the record obtained from the Total Ozone Mapping Spectrometer (TOMS) and the European Global Ozone Monitoring Experiment (GOME) at higher spatial resolution. OMI will also measure total column amounts of several other trace gases, notably NO_2, and information on ozone profiles as well.

EOS Aura will also carry the totally new Tropospheric Emission Spectrometer (TES) instrument for exploratory survey of trace tropospheric constituents. The high spectral resolution (~0.025 cm^{-1}) of the TES instrument will allow vertically resolved measurements of ozone and other trace constituents, including the important nitrogen oxide family that plays a major role in ozone production in the lower atmosphere. Other key tropospheric molecules measured by TES include carbon monoxide and water vapor. TES will operate in both a nadir- and limb-viewing mode, and can be pointed so as to allow observation of interesting regions more than once per day.

The EOS Terra (AM-1) mission will carry another tropospheric instrument the Measurement of Pollution in the Troposphere (MOPITT). This sensor will determine the vertical structure of carbon monoxide (CO) in the troposphere, as well as the total column amounts of CO and methane (CH_4). Combined with other optical measurements on the same platform, MOPITT will determine the relationship between CO concentration, aerosol, smoke, and surface sources such as biomass burning. Partial information on smoke aerosol and the fires responsible will also be available from the Moderate Resolution Imaging Spectrometer (MODIS), another instrument on Terra.

Altogether, the EOS program will provide a vast amount of information on stratospheric chemistry and initiate a new research thrust with the exploration of large-scale chemical processes in the troposphere. From the analysis of EOS data combined with other observations (UARS, aircraft campaigns, and surface-based measurements), NASA expects major advances in stratospheric chemistry that will allow progressing beyond the need for fully comprehensive sets of chemical measurements. In this perspective, future missions will achieve their scientific goals through the interpretation of a representative subset of EOS measurements. The feasibility of this long-term observing strategy hinges on a sufficiently good understanding of the processes which control the relationships between different constituents, under a wide range of geophysical conditions. *In situ* measurements will be essential in acquiring this basic information.

Different sensors, principally imaging radiometers, on several Earth Probes, EOS Terra, Aqua, follow-on operational precursor missions, and operational missions, will continue to provide the background information on the distribution, particle size distribution, and optical reflectance of global aerosols. Relatively thin surface-based networks (AERONET) provide complementary information on aerosol transmission and optical thickness. Solar occultation sensors and limb-scanning sensors (SAGE-IV and follow-on; HIRDLS and NPOESS/OMPS) sample the distribution stratospheric aerosols and provide profile information at relatively wide space- and time-intervals. However, none of these systems is expected to deliver the detailed measurements needed to quantify the radiative forcing of climate by changes in atmospheric aerosol loading. On the other hand, a robust space-based measurement strategy exists to document the changes in solar radiation output that are relevant to the Earth system science, with the required time-resolution, instantaneous precision, and long-term accuracy/consistency.

The next phase of atmospheric chemistry research will marry on-going modeling and intensive studies of specific physical/chemical processes with long-term systematic measurement of a limited range of critical stratospheric trace constituents, focusing on two principal objectives: (1) verifying the recovery of the ozone layer following the projected decrease in anthropogenic halogens and, (2) quantifying climate feedback associated with changes in upper tropospheric and lower stratospheric ozone and water vapor. Tropospheric chemistry, on the other hand, is still a research frontier and progress will require further exploratory global surveys and field studies. Thus, the NASA observing strategy will involve three distinct observing system components: a space-based global mapping component (implemented principally by operational environmental agencies), a space-based precision monitoring component specifically focused on NASA research objectives, and supporting surface-based measurements.

3.3.1.1 Total Column Ozone and Aerosol Mapping

Total ozone data have come principally from the series of Total Ozone Mapping Spectrometer (TOMS), and the Solar Backscatter Ultraviolet (SBUV) measurements on the NOAA polar-orbiting operational environmental satellite series. Both are based on solar ultraviolet backscatter measurements to determine ozone amounts. TOMS is a cross-track scanning instrument that provides daily global mapping of total column ozone with long-term accuracy on the order of 1% per decade. SBUV is a nadir-viewing instrument that provides total column and partial ozone profile data along the sunlit portion of the sub-satellite track, i. e. typically 16 orbits per day.

In addition to total column ozone, TOMS also provides unique data sets on the distribution of aerosol and particulate matter in the troposphere, including sulfate particles and UV-absorbing particles such as mineral dust, volcanic ash, smoke particles from fires and biomass burning. TOMS aerosol data are of particular interest because they currently constitute the only source of information on the large-scale aerosol loading of the atmosphere over land areas. Because they provide information on total column ozone, clouds, aerosols, and surface reflectivity, TOMS measurements are particularly suitable for inferring UV radiation fluxes at the surface of the Earth. A number of "residual techniques" have been developed to infer total tropospheric ozone from TOMS and other (stratospheric) ozone data, especially in the tropics. The method is being validated by an enhanced network of ozone sonde sites in the tropics, under the Southern Hemisphere Additional Ozone Sondes project (SHADOZ). These tropospheric ozone and aerosol observations are helping to prepare for future space-based observation missions dedicated to tropospheric chemistry problems.

The TOMS instrument was flown on Nimbus 7, Meteor-3, ADEOS, and currently on Earth Probe TOMS since 1997. The next TOMS flight, QuikTOMS, is planned for a launch in 2000 aboard a small dedicated satellite. Space-based measurements by other agencies will be important in filling any ozone observation gap. The European Space Agency's GOME instrument has been operating since 1995 and the successor instrument SCIAMACHY on the European ENVISAT mission is expected to provide more comprehensive data, beginning in 2000. NASA investigators played a significant role in the exploitation of GOME data and the development of retrieval algorithms for both GOME and SCIAMACHY. This type of cooperative effort is expected to continue in the future.

Four SBUV/2 instruments are still planned for launch on the NOAA Polar-orbiting Operational Environmental Satellite series in 1999, 2001, 2004, and 2007. In the long term, the US National Polar-orbiting Operational Environmental Satellite System (NPOESS) will deploy an Ozone Mapping and Profiler Suite (OMPS) that encompasses the capabilities of TOMS and will maintain total column ozone measurements as well as ozone profile measurements, both based on observation of backscatter UV radiation. The UV limb scattering technique was demonstrated by the Shuttle Ozone Limb Sounding Experiment/Limb Ozone Retrieval Experiment (SOLCE/LORE) on the Space Shuttle; another space flight is scheduled in 2001 for further refinement of the measurement technique. Likewise, Japan's space agency NASDA is planning to develop a UV backscatter instrument (Ozone Dynamics Ultraviolet Spectrometer) for deployment of a new series of Global Change Observation Missions (GCOM-A) beginning in 2005. A similar ozone profiling sensor (GOME-2) will also be carried by the first two European METOP operational polar-orbiting environmental satellites.

Total Aerosol Loading

Currently, no existing observing technique or combination of techniques can document all relevant aspects of the very complex chemical, microphysical and meteorological processes governing the distribution and properties of atmospheric aerosols. The problem is particularly vexing in the troposphere, where aerosol lifetime is only a few days and their distribution vary widely. A Global Aerosol Climatology Project (GACP) has been established under NASA leadership to analyze available satellite radiance measurements and field observations, infer aerosol distribution and properties, and compile a 20-year global aerosol data set. Determining the global distribution of aerosols and its spatial and temporal variations is an essential element of NASA's climate change research strategy, particularly in order to test and improve aerosol chemistry, microphysics and transport models which will eventually be used to predict the climate impacts of various classes of aerosol. Systematic measurements conducted by NASA include:

- Spatial and temporal distribution of total aerosol loading in the middle and upper troposphere over land and ocean, inferred from the Total Ozone Mapping Spectrometer (TOMS) ultraviolet backscatter measurements (also provides an indication of the nature of the aerosol, e. g. mineral dust versus smoke, etc.).
- Distribution and optical properties of aerosol over land and ocean, inferred from solar reflectance measurements by the Moderate-Resolution Imaging Spectro-Radiometer (MODIS) on EOS Terra and Aqua, and the Multi-angle Imaging Spectro-Radiometer (MISR) on EOS Terra. Measurements of optical depth at several visible wavelengths can be used to derive the Angstrom coefficient which is determined by the aerosol size distribution.

It is anticipated that further progress will be made in satellite retrievals of aerosol distribution, physical properties and chemical composition using a combination of lidar, radiometric and photo-polarimetric techniques. Specific plans for implementation of a comprehensive space- and surface-based global aerosol observing system have not been formulated yet, although some steps have been made by the

GACP. In the short term, the main focus of NASA will be on experimenting with new aerosol observing techniques and exploratory satellite missions (see below).

3.3.1.2 Stratospheric Composition Monitoring

Ozone, Aerosol and Polar Stratospheric Cloud Profiles

The principal source of high resolution stratospheric ozone and aerosol profile data has been the Stratospheric Aerosol and Gas Experiment (SAGE) program, based on the principle of occultation of solar radiation by the limb of the atmosphere. The main limitation of SAGE measurements is spatial coverage, since solar occultations occur only in two latitudes bands for a given orbit. SAGE data have been very useful for determining long-term trends in ozone vertical profile, especially in the lower stratosphere, and SAGE data analysis and trend studies continue to be a research priority. NASA is also currently supporting the systematic analysis of high latitude solar occultation data acquired by the Polar Ozone Aerosol Monitor (POAM-3) instruments on the French SPOT-4 earth observation satellite series (in polar orbit).

Two flight models of an improved SAGE III instrument have been fabricated for deployment on a Russian Meteor-3M spacecraft in the first quarter of 2000 (sun-synchronous polar orbit) and the International Space Station in 2003 (51.5° inclination orbit). Solar occultation from polar sun-synchronous orbits restricts observation to high latitudes only (the lunar occultation capability of SAGE III will help to "fill in" the tropics and mid-latitudes). An additional SAGE III instrument is under consideration, for another flight opportunity not yet determined. It is the intention that this program should merge with the NASA systematic measurement program (see below).

Stellar occultation is a promising technique for ozone profiling, as the multiplicity of stars provides many more occultation opportunities than either the Sun or the Moon and enables greatly expanded spatial coverage. In addition, the point-like nature of stellar sources simplifies the retrieval process. This approach has been successfully demonstrated with the UVISI instrument on the DOD MSX mission (with NASA support for data analysis). NASA has also undertaken the development, under the Instrument Incubator Program, of a more capable and lightweight stellar occultation instrument. Likewise, the Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument on the European ENVISAT mission (launched in 2000) will make use of the stellar occultation technique.

Systematic Stratospheric Chemistry Measurement Program

Verification of ozone recovery and the attribution of observed variations to specific causal factors require accurate systematic measurement of stratospheric ozone, atmospheric temperature, aerosols and polar stratospheric clouds, water vapor, dominant species in the chloride, bromide and nitrogen oxide families, CH_4, N_2O and HF, and spectrally resolved solar ultraviolet radiation in the photochemically active spectral region (200-400nm). There are three basic latitude regions in the stratosphere that are relatively well mixed: the tropics, mid-latitudes and polar regions. Unequivocal verification of stratospheric ozone recovery will require time series of accurate measurements at high vertical resolution (1-2 km) in each of these regions. The centerpiece of NASA's stratospheric chemistry research program is high-precision systematic measurement of trace constituents, aiming for identification of potentially significant species, highest possible accuracy, and long-term consistency, with the minimum sampling density compatible with the science objective.

The nominal concept for the implementation of this program, aiming to maintain key measurements after the completion of EOS Aura, is a two-component observing system consisting of an payload on the International Space Station (ISS) and a series of polar-orbiting spacecraft. The scientific objective would be met by solar or stellar occultation measurements from one (ISS) in an inclined orbit and another platform in polar sun-synchronous orbit. The former would provide occultations in the low to mid-latitude range, the latter at high latitudes. Occultation measurements are essentially self-calibrating and have the potential for excellent long-term accuracy and consistency. A broad-gauge, survey-type instrument (e. g., Fourier transform IR spectrometer) is envisaged to detect the presence and concentration of a wide range of current or potential active compounds. An emission spectrometer would add a very significant enhancement to the horizontal and temporal coverage of the system (See Box 3).

Box 3
Stratospheric Chemistry Survey Mission

The scientific objective of the mission is systematic monitoring of key stratospheric trace constituents, particulate matter, and relevant physical properties, as needed to understand the evolution, stabilization and eventual recovery of the stratospheric ozone layer, as expected from the application of the Montreal Protocol. The program consists of two components:

- International Space Station attached payload for occultation measurements in ultraviolet (SAGE III or SAGE-like instrument) and infrared spectrum (high-spectral resolution Fourier transform spectrometer instrument or equivalent emission sensor). Several instrument payloads will be needed for measurement continuity through the critical ozone stabilization and recovery period, and for payload refurbishment and periodic laboratory calibration.
- A polar-orbiting sun-synchronous satellite series, with the same measurement objectives. Due to orbital geometry, solar occultation from polar orbit provides only limited geographic coverage. The alternative stellar occultation technique would overcome this limitation and provide higher vertical resolution. An emission spectrometer may be added to complement occultation measurements. Emission spectrometry is potentially more informative, enabling the detection of free radicals and much enhanced sampling of the global atmosphere, but is less likely to provide the same vertical resolution and long-term calibration consistency.

3.3.1.3 Systematic Measurement of Total and Spectrally Resolved Solar Irradiance

NASA has taken the lead in long-term measurement of radiant energy received from the Sun. Nimbus-6 measurements, beginning in late 1975 and continuing until 1993, provided the longest data set currently available. Unambiguous evidence of variability in total solar irradiance (TSI) was first obtained from the highly precise Active Cavity Radiometer Irradiance Monitor (ACRIM) radiometer on the Solar Maximum Mission (SMM) in 1980. Monitoring variations in total solar irradiance on climate time scales is a challenging task, because accurate TSI measurements can only be made from space, free from any residual atmospheric absorption, and because changes in TSI are quite small, on the order of 0.1% over a 11 year solar cycle. There is theoretical evidence, however, that considerably larger TSI changes may have occurred in the past, particularly during the Maunder solar activity minimum (1645-1715). The validity of these theories has direct implication concerning the explanation of climate warming since the "Little Ice Age" period.

Identifying trends in total solar irradiance over several solar cycles requires an exacting calibration and/or intercomparison strategy in order to achieve the required long-term consistency with a succession of independent instruments. Relatively large absolute calibration differences may exist between successive instrumental records, certainly much larger than the small relative error margin allowed by the precision and stability of individual radiometers. The NASA strategy is based on:

- Best effort to ensure sufficient overlap between successive TSI measurement missions, so as to enable proper intercomparison between one instrumental record and the next;
- Best possible calibration of each flight instrument against absolute radiometric standards, both in air and in vacuum, and provision for on-board monitoring of instrument aging; and
- Periodic in-space calibration, based on intercomparison of current flight instruments with an identical fresh sensor carried on board the Space Shuttle for a 1-2 week calibration campaign, as insurance against the contingency of early termination before a replacement sensor is in place.

In the near future, two overlapping total solar irradiance measurement missions are planned: the ACRIM Earth Probe mission as part of the EOS program (launch in fall 1999), and the SORCE mission in July 2002 (see Box 4). In the long-term, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program is planning to continue total and spectrally resolved solar irradiance measurements to the required accuracy indefinitely in the future (beginning at the end of the next decade). An additional TSI monitoring mission is being envisaged to bridge the interval between SORCE and NPOESS, if necessary. A supporting research program will be pursued in order to keep the relevant scientific experts involved in maintaining this fundamental data record and encourage further scientific investigations of solar variability. This effort will be strengthened by coordination with similar international efforts, through the establishment of an international investigator group.

Box 4
Solar Irradiance Mission

The Solar Radiation and Climate Experiment (SORCE) mission, planned for a launch in July 2002, is a five-year mission with the following combination of instruments:

- Total Irradiance Monitor (TIM) measuring total (full spectrum) solar irradiance with absolute accuracy of 0.1% or better, and relative precision of 2 x 10^{-5} per year.
- Spectral Irradiance Monitor (SIM) measuring the solar radiation spectrum from 200nm (ultraviolet) to 2500nm (short-wave infrared), with spectral resolution of 1nm for short wavelengths to 25nm for long wavelengths, and absolute accuracy of 2% or better.
- The Solar Stellar Irradiance Comparison Experiment (SOLSTICE), an instrument developed for EOS that will measure the solar ultraviolet spectrum (from 5 to 440nm) with 3% absolute accuracy and 1nm resolution.

In the long term, the NPOESS program is planning to embark a combination of the TIM and SIM solar radiometers developed by NASA, also known as the Total Solar Irradiance Monitor (TSIM), and will continue this measurement indefinitely in the future from the end of the next decade onward. A bridging mission (not yet identified) may be required in the 2005 to 2006 timeframe in order to maintain the continuity of TSIM measurements and ensure adequate overlap with NPOESS.

In relative terms, variability in the ultraviolet (UV) region of the solar spectrum is much larger, on the order of 5%. While variations in solar UV radiation contribute only a small amount to the variability in total solar energy absorbed by the Earth atmosphere, their impacts on stratospheric chemistry and temperature structure (static stability) are substantial and could constitute one of the pathways through which solar variability could induce changes in the Earth's climate. Stratospheric photochemical reaction rates are very dependent upon variable solar ultraviolet (UV) radiation in specific and relatively narrow spectral bands. Changes in UV radiation reaching the surface of the Earth is also likely to impact land and ocean ecosystems. Accurate knowledge of both total and spectrally resolved solar irradiance over several solar cycles is crucial to test the validity of these solar variability theories.

Precise knowledge of spectrally-resolved solar UV irradiance is essential for understanding and modeling these reactions. The two existing records of spectrally-resolved solar UV irradiance were obtained from the SBUV series of instruments on NOAA satellites and two instruments aboard UARS, the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) and the Solar-Stellar Irradiance Comparison Experiment (SOLSTICE). These measurements will be pursued by the SORCE solar radiation monitoring mission in 2002 (Box 4). As a contingency provision against a possible hiatus in spectrally resolved UV measurements, further research will be conducted to develop a more quantitative relationship between solar UV irradiance and proxy indicators of solar activity, such as the 10.7 cm radio-frequency flux.

3.3.1.4 Surface-Based Networks

Systematic measurements from surface-based stations are indispensable, at the current stage of knowledge and observing techniques to validate satellite-derived chemical data and provide otherwise unobtainable information about the concentration of critical trace constituents, especially long-lived chemical species that are well mixed in the troposphere. The objective is to achieve sufficient geographic coverage and sampling density to provide representative information on the spatial distribution and temporal variability of critical chemical species.

Chemical Monitoring Network

NASA surface-based observation activities are carried out in the framework of much larger international programs, notably networks operated by the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) and those coordinated by the Global Atmosphere Watch of the World Meteorological Organization (WMO). Meteorological data are obtained from the WMO World Weather Watch. Other surface data (such as atmospheric concentration of ozone and carbon monoxide, or nitrate and sulfate amounts in rain water) are obtained from pollution monitoring networks operated by regulatory environmental agencies. In this context, NASA's special contribution to ground-based measurement networks is the deployment of research-quality instruments for the determination of long-term trends in atmospheric trace constituent concentration. The main activities are the NASA-sponsored AGAGE (Advanced Global Atmospheric Gases Experiment) and participation in the international Network for the Detection of Stratospheric Change (NDSC). AGAGE provides systematic measurements of surface concentrations of trace constituents, and NDSC probes the chemical composition of the lower stratosphere.

The AGAGE network is based on gas chromatography coupled with mass spectrometry to measure halogen-containing species including hydrochlorofluorocarbons (HCFCs), and bromine-containing species (like halons and methyl bromide), as well as nitrous oxide and methane. There are currently five operating AGAGE stations (Mace Head, Ireland; Trinidad Head, California; Ragged Point, Barbados; American Samoa; and Cape Grim, Tasmania). NASA will continue operating these facilities and will upgrade measurement capabilities and long-term calibration, but does not plan to expand its network. NASA will cooperate instead with other agencies that can maintain research-quality monitoring stations in order to better cover the northern hemisphere.

NDSC is an internationally sponsored program, supported by NASA and several foreign partners, to systematically operate, at a number of sites around the world, surface-based remote-sensing systems that meet mutually-agreed research-quality standards. The instruments deployed at NDSC "primary sites" include visible and infrared Fourier transform spectrometers, millimeter-wave emission spectrometers, visible/UV absorption spectrometers, lidar, and balloon sondes to characterize total column amounts and/or profiles of important species. A very high standard of calibration consistency is maintained between stations and over time through a continuing program of instrument intercomparison in the laboratory and in the field. NASA will continue to seek the cooperation of foreign partners to expand the network in under-represented areas (low latitude regions of Latin America, Africa, and South Asia).

Aerosol Monitoring Network

Systematic observations of total column aerosol content (derived from multi-spectral solar radiation absorption measurements) are carried out by a worldwide network of some 50 monitoring stations (the Aerosol Robotic Network or AERONET) installed by NASA with the cooperation of a number of local institutions. The primary purpose of AERONET is to acquire validation data for global aerosol products inferred from radiometric measurements on the Terra mission.

Ultraviolet Radiation Monitoring Network

The principal source of concern about the depletion of stratospheric ozone is the biological impact of the resulting increase in the flux of actinic (UV) solar radiation that reaches the Earth surface. Scientific knowledge of the solar UV flux at the Earth surface has been long stymied by the absence of suitably calibrated and stable instruments to measure such fluxes. NASA uses the data from a US network of some 60 UV measuring stations (operated by several agencies under the auspices of the US Global Change Research Program) to validate global estimates of surface UV fluxes derived from TOMS observations. The combination of the surface UV network and space-based measurements now provides a means for accurate long-term assessment of changes in surface UV radiation.

3.3.2 EXPLORATORY RESEARCH SATELLITE MISSIONS

The NASA global change research strategy for the next decade is expected to shift from comprehensive surveys of a wide range of chemical surveys (exemplified by UARS and EOS Aura) to more specific process-oriented research satellite missions. At the same time, the emphasis for process-oriented atmospheric chemistry research is expected to shift toward the lower stratosphere and troposphere. The discovery potential of tropospheric chemistry research can justify several experimental Earth Probe missions, each focused on specific process-related science questions.

Tropospheric Chemistry Research Satellites

Like in the stratosphere, large-scale chemical processes in the troposphere are dominated by ozone, which is the key oxidant species. Ozone photolysis is a principal source of the hydroxyl radical (OH) which is the most important agent in the degradation of hydrocarbons. Furthermore, because of its oxidant function, tropospheric ozone causes acute and chronic health problems in humans and attacks plant and animal populations. Ozone is also a greenhouse gas in its own right and contributes to climate radiative forcing, although the impacts are markedly different in the stratosphere and troposphere. The distribution of ozone in the troposphere is influenced by transport from the stratosphere, by regional sources of precursor gases (e. g. biomass burning and urban pollution), and by variations in the atmospheric circulation. Key precursor species include nitrogen oxides, methane and other organic species of anthropogenic and biogenic origins. Both precursor families are subject to the same atmospheric transport which causes a high degree of spatial variability, on scales of hundreds of meters vertically to hundreds of kilometers horizontally.

Two specific challenges need to be addressed to effectively investigate tropospheric chemical processes: horizontal/vertical resolution and temporal sampling. Tropospheric ozone is expected to show considerable vertical stratification and fine horizontal structures that contain information on the origin and age of important species. Likewise, the altitude distribution of upper tropospheric ozone is a critical parameter in climate models. Variability is also important, including significant diurnal variations. On the balance, however, scientific priority was given to vertical resolution over temporal resolution. High vertical resolution will be achievable for ozone with active sounding techniques from low Earth orbit (e. g. differential absorption lidar or DIAL). High vertical resolution observations would be equally valuable for ozone precursors and tracer species, but will probably not be achievable within the time-frame of this plan. Even at relatively coarse vertical resolution, trace species measurements will still be informative in conjunction with high-resolution ozone distribution data for tropospheric chemistry process studies.

High frequency temporal sampling would be best achieved by observation from a geostationary platform. However, the sensitivity and, especially, the vertical resolution of passive radiometric or spectrometric measurement feasible from geostationary orbit is not yet well established and NASA plans to invest in the development of innovative observing technologies to overcome current limitations, in particular, through the New Millennium flight demonstration program.

The planned Triana mission will be the first Earth observing mission to be deployed at the first Lagrange point (L1) - the neutral gravity point between the Sun and the Earth. From L1, Triana will have a continuous view of the sunlit side of the planet. Triana at L1 will complement the current fleet of satellites in low-Earth orbit and geostationary orbit, and will demonstrate the scientific and practical value of the L1 observing location. The Triana Earth Polychromatic Imaging Camera (EPIC) will provide an important complement to Total Ozone Mapping Spectrometer (TOMS) observations and deliver unique data on changes in ozone, clouds, and aerosol from sunrise to sunset for climate science applications and estimation of the amount of UV radiation reaching the surface. Triana’s advanced radiometers will measure the radiances of reflected and emitted energy from a unique range of viewing angles with unprecedented accuracy and will test the current understanding of radiative transfer processes in the atmosphere.

Aerosol Research Satellite Sensors and Missions

Currently, the primary aerosol properties inferred routinely from space measurements are total reflectance and a particle size parameter. The MISR and MODIS instruments on EOS Terra provide more accurate measurements, but still do not allow independent estimates of aerosol radiative forcing, due to the lack of information on aerosol vertical distribution, and optical properties.

The next step will be the PICASSO-CENA experimental satellite mission (in cooperation with the French space agency CNES). PICASSO-CENA will be launched in 2003 together with Cloudsat and fly in formation with Cloudsat and EOS Aqua. The primary sensor of the PICASSO-CENA mission is a dual-frequency, infrared and visible (green), dual polarization lidar profiler that will directly determine the vertical distribution of aerosols over both land and ocean. PICASSO-CENA data, complemented by simultaneous EOS Aqua (MODIS, CERES) measurements, will directly determine aerosol optical depth, number density, and optical properties; they will yield estimates of aerosol radiative forcing essentially free from *a priori* assumptions. The 3-year PICASSO mission will provide a large representative of set of seasonal conditions and geographic regions, but still a relatively discrete sample of the whole atmosphere. It is anticipated that lidar profile data will allow back-tracking the atmospheric trajectories of aerosol layers and help identify their sources.

Solar occultation and limb-viewing measurements also contribute to determining the vertical structure of the aerosols, albeit with poor horizontal resolution. The SAGE IV instrument will include a longer wavelength channel (1.5μm), which affords a better probability of reaching the troposphere. The HIRDLS instrument on EOS Aura will provide spatially dense aerosol profile information derived from emitted atmospheric radiation, free from the geographic coverage limitations of SAGE.

3.3.3 Laboratory Studies and Field Measurement Campaigns

Laboratory measurements of basic physical and chemical properties and processes provide an essential fundamental underpinning for scientific interpretation of field measurements and global satellite-based surveys. First, laboratory measurements of kinetic rates of chemical reactions and photochemical processes, molecular cross sections and quantum yields, and information on heterogeneous processes are needed to understand atmospheric transformations and inform numerical models. Current results of laboratory measurements are critically evaluated in the biennial report on *Chemical Kinetics and Photochemical Data Evaluation*, published by NASA. Second, spectroscopic measurements and related photochemical phenomena are necessary to support NASA's remote sensing projects. Particularly important is the spectroscopy of polyatomic molecules at the temperature and pressure representative of stratospheric and upper tropospheric conditions. Finally, a new range of studies is needed to determine thermodynamic and chemical properties of atmospheric aerosol and their interaction with stratospheric cloud particles, notably the three-component water-nitric acid-sulfuric acid system under stratospheric conditions.

The principal method developed by NASA to understand chemical and physical processes in the atmosphere relies on simultaneous *in situ* and/or remote sensing measurements of related parameters. Troposphere and stratosphere field campaigns are carried out from a variety of platforms, including stratospheric balloons, high altitude ER-2 and WB-57 aircraft, and the DC-8, and P-3 aircraft. Several factors are lessening the traditional specialization of field measurement campaigns for stratospheric or tropospheric studies. First, scientific questions are evolving toward the consideration of phenomena occurring just above and below the tropopause, such as troposphere-stratosphere exchanges. Second, increased flexibility in the operation of several aircraft, notably the ER-2 and uninhabited aerial vehicles (UAVs), now allows access to both the troposphere and the stratosphere with the same equipment. Finally, more capable sensors can be applied to chemical studies, notably measurement of the hydroxyl radical and many key precursor species in the lower stratosphere and upper troposphere. Balloon and aircraft campaigns will be needed in association with EOS Aura to provide detailed photochemical process studies of diurnally varying species that complement the global observations provided by EOS Aura, which will only sample a given latitude at a fixed time of day and to acquire higher precision and spatial resolution data for further process studies.

In the coming decade, growing demands for validation activities in support of space-based atmospheric chemistry measurements and other Earth science disciplines will place a heavy burden on NASA’s aircraft and other non-space facilities. In addition, many important issues in atmospheric chemistry require measurement and analysis at spatial and temporal scales that are not accessible by satellite observation and can best be addressed through a combination of space and non-space measurements. Consultations are underway with the atmospheric science community for planning the Integration of Satellite Calibration/Validation and Research Oriented Field Missions in Atmospheric Chemistry in the Next Decade. An atmospheric chemistry research plan for integration of the research and analysis (R&A) field campaigns and the satellite missions in the next decade will be the end-product of these consultations.

Tropospheric Aircraft Campaigns

Field campaigns undertaken as part of the Global Troposphere Experiment (GTE) have relied on NASA DC-8 and P-3 aircraft for *in situ* and remote (lidar) measurement of ozone, other trace constituents, aerosols and meteorological parameters in remote regions of the world. The focus of these missions was to define the tropospheric background and to look at long-distance impacts of human activities on the troposphere at regional and global scales. The most recent GTE mission was the Pacific Exploratory Mission (PEM) TROPICS-B, implemented in March 1999. Given the relative paucity of process-scale tropospheric chemistry data, further GTE campaigns are in principle scheduled approximately every other year. The focus of these campaigns in the next decade will be on the Pacific Basin, a relatively clean-air region of the world that is adjacent to and will be strongly affected by the very rapid population growth and economic development in Asia. Efforts will be continued during the during this period to enhance the chemically comprehensive suit of measurements on the DC-8 and P-3 through reductions of instrument size and weight, and improvements in sensitivity and temporal resolution. Following up on the GTE initial explorations of general process and chemistry in the major tropical source regions, South America and Southern Africa, light aircraft are being used by NASA and cooperating agencies to address recognized gaps in the understanding of the carbon and nitrogen cycles. These studies include the work of the LBA-Ecology and SAFARI-2000 programs (see Chapter 1).

Stratospheric Aircraft Campaigns

Stratospheric field campaigns usually involve both ER-2 and DC-8 aircraft. Over the past decade, the focus of attention was both northern and southern high latitudes regions were substantial ozone depletion was taking place. More recent campaigns have shifted attention toward mid-latitudes; the most recent Photochemistry of Ozone Loss in the Arctic Region in Summer (POLARIS)campaign, completed in 1997, was aimed at the study of photochemistry in the mid to high-latitude lower stratosphere from spring to late summer. The next major undertaking in the 1999- 2000 timeframe is SAGE III Ozone Loss and Validation Experiment (SOLVE) campaign, integrating space-based (SAGE III), airborne (ER-2 and DC-8) and high altitude balloon measurements.

The SOLVE project is being cited as a paradigm of the type of planning needed to foster scientifically productive flight and R&A programs in the coming decade. The objectives of the SOLVE campaign are to provide calibration and validation data for the SAGE III instrument on Meteor-3M and to evaluate the potential for enhanced ozone losses at high latitudes in the Arctic. The latter objective is driven by recently observed Arctic ozone losses on the same order of magnitude as Antarctic ozone losses. The substantial losses observed during the last decade over the Arctic are not reproduced by current atmospheric models. This inability to quantitatively explain present-day ozone losses undercuts the credibility of model predictions of future ozone losses and recovery under conditions of increased concentrations of greenhouse gases. The synergy demonstrated by SOLVE between space-based and *in situ* measurements, data analysis and modeling studies will guide the conception of atmospheric chemistry field campaigns in the coming decade to serve both satellite remote sensing validation and scientific discovery objectives.

Plans for further field measurement studies beyond SOLVE are open. Candidate projects could include additional aircraft missions focused on Arctic ozone (the first few years of the next century is the period when stratospheric chlorine loading has the greatest potential for ozone destruction) or ones upper tropospheric photochemistry, the properties and effects of gravity waves, the chemical and radiative effects of visible and sub-visible cirrus clouds in the tropics, or troposphere-stratosphere exchange. There is a strong likelihood that one or more aircraft campaigns will organized to acquire validation and/or correlative data for EOS Aura measurements.

The current ER-2 payload has the capability for *in situ* measurement of nearly all important trace constituents in the lower stratosphere, including the important radical species OH, HO_2, NO, NO_2, ClO, and BrO. Together with measurements of source and reservoir gases (such as HCl and $ClONO_2$) and UV radiation, this payload is fully adequate to provide a critical test of photochemical models in the lower stratosphere. Uncrewed Aerial Vehicle (UAV) technology has progressed to the point of readiness for initial science mission demonstrations that will lead to these platforms becoming an important component of the airborne science field campaigns. Unique capabilities of UAVs include long flight duration at altitude (spanning a full diurnal cycle), higher subsonic flight altitudes, and the ability to perform missions that would be hazardous or unsuitable for piloted aircraft. Future UAV capabilities could allow much expanded studies of the 22-25km region of the stratosphere (eventually up to 30km).

Balloon Campaigns

Balloon platforms are typically used to measure the vertical distribution of trace constituents above the ER-2 operational ceiling and have been essential elements of the calibration/validation program for space flight missions such as UARS. Large research balloons can reach altitudes up to 40 km, and carry both *in situ* sensors and remote sensing instruments. The Observations from the Middle Stratosphere (OMS) instrument payload was initially developed for comprehensive *in situ* stratospheric measurements, predominantly measurements of tracer concentrations. Since then, the addition of several remote-sensing instruments allows OMS to provide measurements of the complete suite of free radicals, source, reservoir, and tracer species needed for detailed process studies. It is foreseen that balloon flights will continue over the next few years, in conjunction with stratospheric aircraft campaigns. Development of new balloon capabilities (for example, ultra long-duration flights) may expand the range of high altitude balloon investigations. Balloon measurements will play a critical role in the SOLVE campaign.

In situ and Surface-based Aerosol Process Studies

Field campaigns, involving coordinated use of multiple aircraft platforms, surface- and satellite-based measurements, are an integral component of the program. Each field experiment is a coordinated effort with the activities sponsored by other US federal agencies and international institutions. For example, the Smoke, Clouds and Radiation (SCAR) experiment series was designed to obtain simultaneous *in situ* and remote measurements of the physical and chemical properties of aerosols produced by biomass burning and other human activities. The SCAR field studies also generated data for the evaluation of MODIS-compatible remote sensing algorithms. SCAR experiments were conducted in 1993 (effect of industrial pollution over the Atlantic seaboard), 1994 (biomass burning in California and Oregon), and 1995 (biomass burning in Brazil). Future plans for further field campaigns are yet to be determined, especially in relation to the validation of MODIS, MISR, and PICASSO-CENA aerosol products.

3.3.4 MODEL DEVELOPMENT AND STUDIES

Model development, validation and simulations are critical to nearly all aspects of atmospheric chemistry, as they provide the vehicle through which observations are interpreted and understanding of atmospheric processes can be tested. Models also constitute the principal tool for assessing future impacts on atmospheric composition. It is convenient to group model studies in three categories: process modeling, application to retrospective analysis, and model predictions.

Process Models

Process models are designed to provide the best possible representation of selected atmospheric processes. Various types of models are used for different classes of chemical processes, including (i) constrained photochemical models with the fullest possible representation of all constituents and chemical processes within a fixed air mass, (ii) aerosol microphysics models providing a detailed description of new particle formation, transformation and loss by gravitational settling or entrainment in clouds, (iii) parcel trajectory models that simulate the evolution of one or a number of air parcels as they move through the atmosphere, (iv) radiative transfer models for computation of radiation flux (especially ultraviolet and visible) in the atmospheric column, taking into account absorption and scattering by trace gases, aerosols, clouds, and the underlying surface, and (v) dynamical models that simulate the formation and propagation of waves created by various sources. Process models are typically constrained by comprehensive data sets from intensive field measurement campaigns. The ability to accurately reproduce observed phenomena constitutes a critical test of our understanding of the particular processes represented in such models.

Retrospective Models

These models are designed to simulate the past evolution of trace constituent and/or aerosols given the strength of surface sources and sinks (or boundary conditions). The models may be utilized to reproduce changes in trace constituents in response to time-dependent meteorological forcing and sources, or simulate long-term equilibrium conditions as a function of changing boundary conditions (surface halogen abundance, solar input, etc.) or other constraints (e.g. sulfate aerosol distributions). Short simulations require that meteorological fields be specified for the time period of interest; this information is typically derived from meteorological data assimilation systems or forced dynamical models (e.g. stratospheric models forced with known tropospheric meteorology, or tropospheric mesoscale models forced by far-field conditions). Over longer time periods, the actual interannual variability may be ignored, although attempts have been made to take it explicitly into account. The requirement for boundary conditions or basic meteorological data ties atmospheric chemistry research to the global water and energy cycle component of the NASA Earth science program (See chapter 4). It is foreseen that interactive 3-dimensional transport-chemistry models will soon be widely utilized for extended simulations and/or predictions.

It is also anticipated that more attention will be given to the application of data assimilation methods to atmospheric chemistry variables. Current efforts in this area include assimilation of long-lived stratospheric tracers (UARS data), ozone and tropospheric carbon monoxide concentration. A related application is "inverse modeling", i. e. the process of using chemical constituent observations with an atmospheric model to infer information about model processes that affect the distribution of these constituent. This technique has been applied to studies of chlorofluorocarbon sources and sinks. It is anticipated that the technique will soon be expanded to constituents with more complex sources and sinks distributions, such as carbon monoxide and methane.

Model evaluation is a strong activity in the NASA program, based on the comparison of model outputs with measurements. Such efforts include the "Models and Measurements" intercomparison completed in 1998. This effort, conducted jointly by the Office of Earth Science and the Office of Aero-Space Technology, was a critical test of the ability of various model to reproduce observed phenomena under prescribed conditions. Measurements of indicators of the stratospheric age of air parcels (CO_2 and SF_6,) have proven valuable for diagnosing inadequacies in model transport. Observations of conservative tracers such as NO_y and Cl_y, along with the radical species, have been used to test the accuracy of component chemical mechanisms in models. Models have trouble simultaneously simulating the age of both the air and chemical tracers. Comparisons with measurements of species which are produced only in the stratosphere, such as the isotopes ^{7}Be and ^{10}Be, will help resolve this issues. Such efforts are expected to continue in the future, with a shift in priority toward tropospheric chemistry. NASA also expects to continue supporting the intercomparison studies undertaken under the aegis of the Global Integration and Model component of the International Global Atmospheric Chemistry (IGAC) program.

Predictive Models

Prognostic models are designed to simulate the future evolution of the atmosphere. In many cases, these models are substantially similar to those used for retrospective studies. In the prognostic mode, however, meteorological fields must either be assumed from some future atmospheric circulation scenario (typical method in two-dimensional models) or from a three-dimensional general circulation model (GCM). The use of GCMs will be particularly important in simulations of the combined response of the atmospheric circulation and chemistry to climate change, as the dynamical state of the atmosphere may change significantly. Such models will provide the means to assess the feedback mechanisms between chemistry, radiation, transport, and eventually biospheric processes and feedback. Considerable work remains to be done to develop fast chemistry and microphysics algorithms for use in time-dependent models, as well as high performance numerical integration schemes for core dynamics (see section 2.3.4). Additional speedup will accrue from the use of massively-parallel computers (at non-trivial cost in software complexity and lack of flexibility).

Model-Based Assessments

The atmospheric chemistry community has a long history of supporting atmospheric environment impact assessments. The most widely known are the periodic Scientific Assessments of Ozone Depletion, carried out on behalf of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) as well as the assessment of climate forcing factors on behalf of the Intergovernmental Panel on Climate Change (IPCC, 1995). Additional studies have been organized by the Office of Aero-Space Technology to assess the impact of projected supersonic and subsonic aircraft fleets on the atmosphere. A special assessment of the atmospheric effects of aviation is currently being carried out for the IPCC, on behalf of the International Civil Aviation Organization. The international research program on Stratospheric Processes and their Role in Climate (SPARC) under the World Climate Research Program also organized assessments of changes in the vertical distribution of ozone. SPARC produced an updated assessment of trends in stratospheric temperature, which was incorporated in the Trends in Stratospheric Temperatures section of the 1998 Scientific Assessment of Ozone Depletion (WMO, 1999). SPARC is likewise sponsoring an analysis of the variability and trends in stratospheric water vapor. Predictive and equilibrium atmospheric chemistry models are an essential tool for this purpose. NASA expects to continue supporting these important applications of knowledge acquired in the ESE atmospheric chemistry program.

Aerosol Impact Assessment Models

Given current state of knowledge, the most practical means to estimate the global radiative impact of anthropogenic aerosols (or a particular class of aerosols) and gauge the relative importance of anthropogenic and natural emissions in the global aerosol distribution, may be the numerical simulation of atmospheric transport, aerosol formation and evolution, and radiative transfer. The problem is to improve the degree of confidence in such models at the level of the representation of basic microphysical and chemical processes (local process studies), and at the level of global model simulations (global model product validation).

Unlike clouds, aerosols appear with a large diversity of chemical compositions, physical properties and derived radiative characteristics. Chemical, physical and radiative properties are closely linked to the specific sources of the aerosols. Complete aerosol emission inventories are a crucial input for the advancement of coupled climate-aerosol model simulations. Since radiative properties of aerosols are strongly linked to their size distribution, it is essential that the distribution of water vapor and the growth of aerosol particles as a function of relative humidity be properly characterized in the models. Satellite measurements can be used to constrain models of both the direct and indirect radiative forcing by anthropogenic aerosols. However, it is fair to say that a comprehensive strategy does not yet exist for systematic refinement, testing and validation of current global aerosol models.

3.4 LINKAGES

Linkages with other NASA programs

Understanding the long-distance transport and dispersion of trace species in the troposphere and stratosphere is dependent upon progress in knowledge of the atmospheric circulation (notably through 4-dimensional physical data assimilation) and the ability to realistically simulate atmospheric dynamics with general circulation models. Conversely, assimilation of tracer data is a promising avenue for progress in the analysis of the global atmospheric circulation. Another important linkage is the study of interlocking physical and chemical processes that control aerosol formation, transformation and removal. These scientific issues are being studied from the perspective of both atmospheric chemistry and physics (Chapter 3 and 4, respectively). Both aerosol and trace atmospheric gases have significant impact on atmospheric radiation transfer. The radiative impact of these atmospheric constituents represents a major linkage between atmospheric chemistry and global climate change, that must be factored in climate change prediction and assessments (Chapter 7).

Many important trace species have biological sources in the ocean or over land. Quantifying these emissions and understanding the terrestrial or marine processes that govern the release of trace constituents to the atmosphere is a scientific issue of interest to both atmospheric chemistry and the biogeochemistry of ecosystems (Chapter 2).

The Atmospheric Chemistry program also cooperates with the Aero-Space Technology Enterprise in the assessment of the potential effects of subsonic and supersonic aviation on climate and the global environment, including engine emission of effluents that affect the concentration of ozone, and particulate matter and aerosol precursors that affect the formation of condensation trails and clouds.

Linkages with other US agencies

The NASA Atmospheric Chemistry research program maintains a very active cooperation with the National Oceanic and Atmospheric Administration (NOAA) Environmental Research Laboratories (ERL) for the conduct of airborne campaigns and surface-based measurements. NASA and NOAA have developed complementary monitoring networks for accurate measurement of the surface concentration of long-lived trace constituents. The NOAA flask sampling network has a broad geographic coverage and collects weekly samples that are analyzed at a central facility in the US. The NASA Advanced Global Atmospheric Gases Experiment (AGAGE) network operates only a small number of stations distributed in latitudes, but makes much more frequent (hourly) measurements at the sites themselves. The two agencies organize detailed intercomparison between the two networks to ensure their consistency.

NASA and NOAA collaborate in the joint exploitation of ozone data obtained from operational SBUV and TOMS sensors. In the same context, NASA cooperates with DOD and NOAA for the development of the advanced Ozone Mapping and Profiler Suite (OMPS) of instruments that will fly on the National Polar-orbiting Operational Environmental Satellite System (see section 4.3.1.1). NASA also actively cooperates with several DOD research establishments, notably the Naval Research Laboratory (NRL) for the exploitation and scientific analysis of measurements obtained by the NRL Polar Ozone & Aerosol Monitor (POAM) embarked on a French SPOT Earth observation satellite.

International linkages

Atmospheric chemistry, especially in relation with the depletion of stratospheric ozone and changes in the concentration of greenhouse gases, has high international visibility. The NASA atmospheric chemistry program has been a major contributor to scientific advances in characterizing the causes of ozone depletion, which led to the *Montreal Protocol on Substances that Deplete the Ozone Layer* and subsequent amendments. NASA maintains the observing capability to monitor stratospheric ozone and actively contributes to periodic international assessments of the state of the ozone layer commissioned by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). NASA also contributed to the Intergovernmental Panel on Climate Change (IPCC) assessment of the climatic impacts of ozone and other greenhouse gases, the IPCC/ICAO Special Report on Aviation and the Global Atmosphere. Likewise, NASA is a major partner in international cooperative research initiatives organized by the international World Climate Research Program, particularly the study of Stratospheric Processes and their Role in Climate (SPARC), and the International Geosphere-Biosphere Program, particularly the IGBP International Global Atmospheric Chemistry core-project.

Bilateral cooperative programs or projects have also been developed with many foreign agency partners. Original instruments developed by Germany (CRISTA), the Netherlands (OMI), Canada (MOPITT) or in cooperation with UK (HIRDLS) will fly on several EOS missions or the International Space Station. Furthermore, NASA has been actively cooperating with the European Space Agency in the joint analysis of data from ESA's Global Ozone Monitoring Experiment (GOME) sensor and supports US co-investigators selected by ESA for its ENVISAT mission. NASA also maintains similar scientific collaboration with Japan, notably through joint announcement of research opportunities for the ADEOS and ADEOS-2 missions. Finally, NASA plays a leadership role in the Network for Detection of Stratospheric Change (NDSC) that operates a variety of advanced remote sensing instruments for monitoring stratospheric ozone and other atmospheric constituents in partnership with NOAA, NSF and many foreign institutions (see section 4.3.1.4).

3.5 REFERENCES

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CHAPTER 4

GLOBAL WATER AND ENERGY CYCLE

4.0 INTRODUCTION

The cycling of water in the Earth's atmosphere is the process that constantly renews fresh water resources, a feature unique to our planet. As civilizations evolved, the human population, agriculture, and industry have placed ever-increasing demands on water resources and, by now, significant change in the global hydrologic regime would entail serious consequences in many regions where water resources are already strained.

The National Research Council report on *Research Pathways for the Next Decade* recognized the global water cycle as a central research issue of global environmental change: "Water is at the heart of both the causes and the effects of climate change. It is essential to establish current rates of, and possible changes in precipitation, evapotranspiration, and cloud water content… Better time series measurements are needed for water runoff, river flow and… the quantities of water involved in various human uses" (NRC, 1999). Ascertaining the rate of cycling of water in the Earth system, and detecting possible changes, is a first-order problem as regards the renewal of water resources.

Rainfall and subsequent fast hydrologic processes are directly linked to the development and life cycle of weather systems. Conversely, the latent heat transported and released by the global water cycle is the principal source of energy that drives the atmospheric circulation and weather disturbances, over periods of hours or days, and horizontal scales of 10-100 kilometers. Thus, a fundamental problem is that of relating planetary-scale climate variations or change to regional weather and fast hydrologic processes that directly control water resources. Scientific progress in this domain is critically dependent upon the ability to observe the atmosphere and Earth surface at high spatial and temporal resolution, and the ability to handle the resulting large data flows and long time-series. NASA capabilities are well suited to undertake both tasks.

Net radiation absorbed by the Earth's surface is the energy source that drives evaporation and, in general, the global water cycle. In this respect, water and energy exchanges are complementary aspects of the same global process. Furthermore, water in the form of vapor, cloud ice or cloud liquid water, controls atmospheric radiation transfer, the planetary radiation balance, and climate. In the words of the Intergovernmental Panel on Climate Change (IPCC, 1996): "Uncertainties in modeling cloud-radiation interactions are the largest factor in determining the range [of climate warming]". A decade of scientific research and technology development conducted under NASA's Earth Observing System (EOS) program has enabled embracing the spatial diversity and complexity of these cloud and radiation feedback processes (EOS Science Plan: *Radiation, Cloud, Water Vapor, Precipitation and Atmospheric Circulation*; NASA, 1999).

This cross-cutting research theme builds upon the progress made by the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program, and the Biospheric Aspects of the Hydrological Cycle (BAHC) project of the International Geosphere-Biosphere Program. The goals of NASA in this domain are to conduct an interdisciplinary research effort in cooperation with USGCRP partners, and make key scientific contributions based on NASA's unique capabilities for global observation, data analysis and Earth system modeling. The overarching goal is to improve the understanding of the global water cycle to the point where useful predictions of regional hydrologic regimes can be made. This predictive capability is essential for practical applications to water resource management and for validating scientific advances through the test of real-life prediction.

4.1 MAIN SCIENCE QUESTIONS

- ***How are global precipitation, evaporation, and the cycling of water changing? (Variability)***

According to model predictions, the most significant manifestation of climate change would be an acceleration of the global water cycle, leading to increased global precipitation, faster evaporation and a general exacerbation of extreme hydrologic regimes, floods and droughts. Since the release of latent heat associated with condensation is the principal source of energy for rapid cyclogenesis, a more active water cycle would generate more frequent and/or more severe weather disturbances. Paleoclimatic and historical records indicate the occurrence of devastating floods and droughts in past times but these ancient hydrologic events do not constitute compelling evidence of global change in the hydrologic cycle, as most regional anomalies are just manifestations of local weather variability. Knowledge of global atmospheric energy and water budgets, as well as global precipitation, is needed in order to investigate the existence of significant global trends in the rate of the water cycle.

- ***What are the effects of clouds and surface hydrologic processes on the Earth's climate? (Response)***

The overall response of mean climate properties to changes in external forcings is the result of a multiplicity of non-linear "fast climate processes" that evolve on meteorological time-scales in the atmosphere and at the surface of the Earth. Such processes ultimately determine time- and space-averaged climate properties and the relationships between these properties. On the other hand, empirical relationships between climatological mean properties provide little insight in the underpinning fast physical, chemical and biological processes that govern momentum, energy and water exchanges in the climate system. Knowledge of these basic processes is essential to extrapolate confidently model simulations from current climate conditions to significantly different states of the Earth system. The problem is integrating the results from observation and model studies of cloud systems, atmospheric boundary layer turbulence, land surface processes and watershed hydrology, and surface fluxes over ocean and continents in order to develop reliable mathematical representations of these small-scale physical processes in atmospheric circulation and climate models.

- ***How are variations in local weather, precipitation and water resources related to global climate variation? (Consequences)***

A critical problem of climate science is that of relating changes in global-mean climatological state to variations in the probability and intensity of weather phenomena, and related changes in precipitation, hydrologic regimes of river basins, and fresh water resources. Soil moisture, accumulated snow, and the freeze/thaw transition control evaporation, surface temperature, and climate as well as the growth of plants. This new climatic outlook at hydrology, enabled by global observation of hydrologic parameters from space, aims to achieve quantitative predictions of precipitation and run-off on all spatial scales, from global to the scale of individual river catchments that are relevant to water resource management. Essential for achieving this objective is the capability to observe and model the global atmospheric circulation and land surface hydrology at much higher spatial resolution than is currently practical with climate models.

- ***How well can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?*** **(Prediction)**

Accurate forecasting of weather has major significance for the protection of lives and property. Thus, improving the accuracy of short-term predictions and increasing the period of validity of long-range forecasts is of great practical interest and is also a great scientific challenge. Scientific advances in climate and/or atmospheric general circulation models, and more effective methods for ingesting new types of observations, are directly applicable to the improvement of operational forecasting systems. Conversely, experience has shown that synergy with operational weather forecasting is a powerful engine of progress for both the verification of new scientific concepts and the development of new observing systems or products.

4.2 NATURE AND SCOPE OF THE SCIENTIFIC PROBLEM

Evaporation, precipitation and the transport of water in the Earth's atmosphere are the controlling processes that redistribute energy from the Sun, drive the atmospheric circulation and renew fresh water reserves. Current knowledge of these complex processes is not accurate enough to predict with confidence the amount of rain nor the mass budget of water reservoirs.

4.2.1 Global Water Cycle Variability and Trends

A statistically meaningful rise in global mean temperature (with significant regional differences) has been observed at the surface of the Earth during the last century, particularly the last two decades. Surface warming implies a rise in the temperature of all or part of the atmospheric column, an increase in atmospheric water content, and changes in atmospheric circulation that are manifested by a global pattern of warming and cooling. While still relatively small, such large-scale or global climate changes can and do entail changes of much greater significance in regional weather, ecosystem productivity, water resource availability, and other attributes of the environment.

Atmospheric temperature implicitly determines the large-scale atmospheric flow, including dynamical instabilities that are at the origin of weather phenomena. Atmospheric water vapor is the principal vehicle of the atmospheric energy that drives the development of weather systems and the source of precipitation. Further, water vapor is a strong absorber of terrestrial radiation; increased atmospheric moisture associated with warmer air has a powerful amplifying impact (positive feedback) on the greenhouse effect. Global temperature and moisture profile measurements are obtained routinely by operational environmental satellites, but the existing operational measurements do not provide the accuracy and consistency required for climate research. Improved measurements are required to address this scientific problem and would also be of direct benefit for weather forecasting applications.

Global precipitation is the principal indicator of the rate of global water cycle, and can also be used effectively as an input for numerical weather forecasting. Together, the atmospheric water content and global precipitation rate determine the residence time of water in the atmosphere. Precipitation data, obtained routinely by a worldwide network of land-based raingauges, show evidence of increasing rainfall rates in some regions. In other regions, notably the tropical oceans, knowledge of precipitation rates is poor due to the limited observational base. Establishing the existence of a global trend requires homogeneous global rainfall information that can only be assembled from a combination of surface-based and space-based measurements.

Closing the water budget over all regions of the world is the ultimate objective of water and energy cycle research. Indeed, knowledge of net fresh water fluxes over the world oceans is indispensable not only to close the atmospheric leg of the global water cycle, but also to quantify fresh water inputs or losses that control ocean water salinity and density. The "buoyancy flux" associated with net fluxes of heat and fresh water is the principal driver of the deep ocean circulation. Likewise, changes in regional precipitation and evaporation drive variations in hydrologic regimes, water resources, and soil moisture available for plant growth. Over polar and high altitude regions, solid precipitation (snowfall) minus sublimation, snow and ice melting, or iceberg discharge control the mass balance of glaciers and polar ice sheets, the latter containing a significant fraction of the Earth's total reserve of free water. The overall goal is to deliver reliable estimates of precipitation minus evaporation over the whole surface of the Earth, likely from a combination of measurements (principally precipitation) and model estimates (principally evaporation).

4.2.2a Water Vapor, Clouds, and the Planetary Radiation Balance

Water vapor strongly absorbs infrared radiation and provides by far the largest contribution to the atmospheric greenhouse effect, nearly 90 Watt/m^2 compared to 30 Watt/m^2 for all other absorbing trace gases present in the atmosphere. Furthermore, atmospheric humidity is highly variable and responds strongly to changes in atmospheric temperature, thus inducing a potent feedback mechanism that tends to amplify climate change. However, the physical processes that control the distribution of water vapor are not known well enough to ascertain beyond doubt whether, for example, deep convection has a net moistening or drying effect on the upper troposphere. Existing water vapor data are neither accurate nor comprehensive enough to establish the existence of a systematic trend associated with global climate change.

Liquid water or ice clouds profoundly affect the planetary radiation budget: clouds contribute about 50% of the planetary albedo, and absorption of terrestrial radiation by cloud is equivalent to all greenhouse gases other than water vapor. Clouds also are the principal factor controlling instantaneous radiant energy fluxes that are absorbed by the atmosphere or the Earth surface. Radiative heating or cooling of the atmosphere cause air parcels to rise or sink and, in general, trigger convective motions. Net radiation absorbed by the Earth's surface is the basic energy source that drives evaporation, and fuels photosynthesis. Because of the complexity of cloud microphysical processes and extreme variability of cloud systems, the goal of relating the radiative impact of clouds to basic physical knowledge has eluded us so far. The formation, life cycle and optical properties of cloud systems remains, to this day, the largest source of uncertainty in simulations or predictions of global climate change. Clouds affect climate both directly, through their controlling effect on the planetary radiation balance, and indirectly, through vertical transport and condensation of water vapor that controls upper-tropospheric moisture and its greenhouse effect. Conversely the formation, life cycle and radiative properties of clouds are governed by the relative humidity of surrounding clear air.

Cloud processes involve complex 3-dimensional interactions between fluid dynamical motions, microphysical and optical properties of liquid and ice cloud particles, pre-existing condensation nuclei (aerosols), and the dynamics of the mesoscale weather systems in which they are embedded. These complex interactions generate extremely diverse cloud systems and cloud types, each involving different controlling microphysical and meteorological factors. Understanding these complex phenomena requires observations that simultaneously (1) resolve the 3-dimensional structure of cloud systems, (2) cover a representative sample of all different cloud types, (3) characterize large-scale weather patterns or mesoscale disturbances that generate the clouds, and (4) relate cloud system structure and properties to large-scale climate variables, especially divergent winds in the troposphere and radiation fluxes at the top of the atmosphere. These observational requirements have only been partially met so far by field observation campaigns focused on one or a few cloud types. NASA is preparing a major space-based exploratory program, involving a constellation of three experimental satellites, to provide for the first time this full range of observations.

4.2.2b Surface Hydrology, Water Resources and Biospheric Processes

Fresh water is an essential ingredient of life, indispensable to all terrestrial species and an essential resource for agriculture. Water also plays a unique and almost irreplaceable role for a very broad range of domestic applications and industrial processes. For these reasons, fresh water is an immensely valuable resource on which our existence depends. The long-range transport of water vapor by winds, condensation and precipitation, the partitioning of rainfall between ground water storage and river runoff, and evapotranspiration from vegetated areas, all contribute to determining the fresh water budget of land areas, and the fate of water reserves available to terrestrial ecosystems and human societies. These diverse phenomena have yet to be quantified with sufficient accuracy to enable applying existing climate predictions to flood forecasting and water resource management.

The ***surface hydrologic processes*** that govern continental water budgets and the availability of fresh water resources are the result of complex physical and biological processes taking place at the land surface. So far, basic hydrologic processes have been examined mainly at the scale of relatively small river basins or catchments. Quantitative understanding of hydrologic processes over large areas, commensurate with the scale of climate phenomena, will require a breakthrough in large-scale observation of hydrologic properties and physical climate drivers. Specific observational requirements to address this problem include (in addition to atmospheric properties, precipitation and surface radiation fluxes) exploratory measurements of soil moisture, snow accumulation, and the transition between frozen and thawed soil conditions.

From a broader perspective, the Earth system can be envisioned as consisting largely of interconnected cycles for water, energy, and carbon. Hydrologic processes play a central role in connecting the three cycles across land, atmosphere and ocean. Soil moisture controls land evaporation and plant transpiration, two processes that links the fluxes of energy (radiant and latent heat), water and carbon between land and atmosphere. River flow carries nutrients and sediments to estuaries, providing an effective link between terrestrial and oceanic systems. Traditionally Earth sciences have progressed along disciplinary lines that address research questions within one geographical domain and often only one (or two) of the above cycles. As our interdisciplinary understanding of the Earth system progresses, many productive science questions are emerging concerning the interfaces between the water, carbon, and energy cycles and between the atmospheric, terrestrial, and oceanic domains.

4.2.3 Climate-Weather Connections

Weather disturbances and, in general, the atmospheric circulation govern the distribution of clouds, their water content, precipitation yield and radiative properties. It is not sufficient, for climate predictions, to study atmospheric or land surface processes in isolation from the atmospheric circulation which controls the water and energy inputs to these processes. Such connections are transient and can only be understood, modeled, and validated through direct comparison of meteorological and hydrological model products with observations at the same place and time. This opportunity is lost when research is limited to studies with atmospheric circulation models unconstrained by observed initial values.

To what extent are variations in local weather, precipitation and water resources related to global climate change? The striking manifestations of "El Niño weather" are clear examples of the linkage between a large-scale or global climate anomaly and changes in regional weather patterns. Much remains to be learned, however, about the relationship between observed trends or anomalies in global-mean atmospheric state and changes in the path, frequency and intensity of weather systems. The broad scientific challenge is that of relating the large-scale atmospheric circulation to the dynamics and life cycle of mesoscale storms (e. g. hurricanes) and other severe weather systems (e. g. tornado-generating rainstorms), and then predicting how that relationship might change in different future climates. The specific challenge is that of deriving quantitative precipitation predictions from global and/or mesoscale weather models. Both topics are also central objectives of the US Weather Research Program.

A major anticipated impact of global climate change is change in the frequency and severity of regional floods and droughts, the availability of water resources, and the volume of inland water bodies (e. g. the Caspian sea). Again, the principal driver of these changes is precipitation, but knowledge of large-scale changes in soil moisture, snow accumulation, seasonal soil freeze/thaw transitions, and the stage height of large rivers and inland water bodies, is also required to gain quantitative insight in the hydrologic consequences of climate variability and change. As competition for water resources rises, this information will become increasingly valuable for rational management of limited water resources.

4.2.4 Extended-Range Weather Prediction

Improving the accuracy of short-term forecasts and increasing the period of validity of long-range predictions both are of great practical interest for the protection of lives and property. Both objectives are also great scientific challenges. Thus, the question arises: To what extent can weather forecasting be improved by new global observations and advances in satellite data assimilation?

Twenty years ago, meteorologists had their first opportunity to use of global satellite observations collected for the scientific purpose of demonstrating the feasibility of one-two week weather prediction using computer models of the atmosphere. We are now finally on the verge of achieving this objective, thanks to successive breakthroughs in global weather observations, atmospheric circulation models, and data assimilation methods used for ingesting observations into such models.

Space-based measurements can only detect radiation emerging from the earth's atmosphere, not determine directly the meteorological properties of interest. The interpretation of satellite measurements is basically a two-step mathematical procedure: (1) inferring the properties of the atmospheric medium from the observed radiation signature, and (2) merging the new data with other measurements at different locations and times, including information from past measurements that is contained in the current predicted state of the atmospheric circulation. These two steps may be combined into a single retrieval/4-dimensional assimilation process, as computing capabilities would permit. In-depth knowledge of the physics of the measurement is essential for succeeding in the first task, that can be provided by instrument science teams associated with NASA development projects.

While weather prediction is the primary responsibility of operational environmental agencies, such as NOAA in the US, scientific advances made by NASA in the development of new observation techniques, more realistic climate or Earth system models, and more effective methods for ingesting new types of observations, are directly applicable to the improvement of operational forecasting systems. Experience has shown that synergy between operational weather forecasting practice and the development of new observation systems or products is an effective engine of progress for both. The principal thrusts of ESE's cooperation with operational weather services are (1) participation in the development of precursor operational instruments for application to various operational environmental satellite systems, (2) development of new data products originating from space-based observing systems, and (3) collaboration in the development and experimentation of improved atmospheric circulation models and data assimilation schemes.

EXPECTED SCIENTIFIC ACHIEVEMENTS

Question 1: How are global precipitation, evaporation, and the cycling of water changing?

Expected new knowledge in the next 5 years

- Decadal trend in total precipitable water over the oceans, based on a ten-year global data set of microwave radiometric measurements;
- Baseline 3-dimensional distribution of water vapor in the global atmosphere;

Expected new knowledge in the next 10 years

- Decadal trend in the water vapor content of the global troposphere (by altitudes and regions) based on a ten-year high-resolution data set;
- Decadal trend in global rainfall rate, based on a ten-year data set.

Question 2: What are the effects of clouds and surface hydrologic processes on the Earth's climate?

Expected new knowledge in the next 5 year

- Global statistics of 3-dimensional cloud structure and cloud particle properties over a representative set of weather systems; and impacts on the planetary radiation budget;
- Cloud Ensemble Model simulations of cloud dynamics and microphysics and application to parametric representation of clouds in climate models, especially tropical cirrus clouds.

Expected new knowledge in the next 10 years

- Model representation of radiation transfer in the cloudy atmosphere and estimation of surface radiation at the level of accuracy needed for predictions of regional climate change;
- Indirect radiative forcing due to the effect of aerosols on cloud radiative properties.

Question 3: How are variations in local weather, precipitation and water resources related to global climate variation?

Expected new knowledge in the next 5 years

- Relationship between sea surface temperature anomalies and tropical cyclone frequency;
- Relationship between global anomalies in surface boundary conditions and extra-tropical storm tracks, continent-scale precipitation, and river discharge.

Expected new knowledge in the next 10 years

- Relationship between seasonal anomalies in surface boundary conditions and ocean heat content and tropical cyclone intensity/precipitation;
- Time-dependent distribution of soil wetness over continents and estimation of volumetric soil moisture;
- Linkages between anomalies in land and sea surface conditions and regional or catchment-scale precipitation, soil moisture, and river discharge;
- Effects of the soil freeze/thaw transition on continental scale hydrology and ecosystems.

Question 4: How well can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?

Expected new knowledge in the next 5 years

- Impact of improved (1°C/1km) temperature profile accuracy on weather forecasting skill;
- Impact of high-resolution ocean surface wind observation on the prediction of storm paths and storm strength;

Expected new knowledge in the next 10 years

- Impact of advanced atmospheric general circulation models and data assimilation methods on the skill of extended-range weather prediction
- Impact of global precipitation observations on the prediction of river flow and water resources.

4.3 NASA PROGRAM ELEMENTS

The pathway toward understanding the global water cycle and ultimately its role in climate is an integrative research strategy covering a range of atmospheric and land hydrological processes, which all have in common their dependence upon the atmospheric circulation and weather disturbances. Because of the short time-scales and spatial variability of meteorological phenomena, high resolution and frequent observations are needed, which places a heavy observational burden on the program, as emphasized in the EOS Science Plan, Chapter 2: *Radiation, Clouds, Water Vapor, Precipitation, and Atmospheric Circulation* (NASA, 1999).

Investigating trends in the rate of the global water cycle and atmospheric climate in general requires primarily consistent time series of global atmospheric temperature, moisture and precipitation data. To achieve this objective, significant improvement is required in the quality of basic atmospheric and hydrologic data sets acquired systematically by national environmental agencies. NASA will contribute to this enhancement by transferring scientific know-how and technical innovations from research programs to operational observing systems when the opportunity arises, such as the development of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The main thrusts will be (1) participation in the NPOESS Preparatory Project, including the development of an Advanced Technology Microwave Sounder, and (2) the realization a multi-satellite global precipitation measuring mission (Section 4.3.1).

The capability to accurately model the radiative effect of water vapor and clouds is a crucial requirement for climate predictions. The largest source of uncertainty in model simulations of global climate change is currently the representation of radiation processes in the cloudy atmosphere, characterized by the great complexity of radiation transfer physics, and spatial heterogeneity at all scales, from cloud particles to individual clouds and cloud systems associated with weather disturbances. NASA research will build on an already strong atmospheric radiation science program and focus on the study of generic cloud processes through (1) experimental satellite missions that aim to characterize the vertical structure of cloud systems, (2) *in situ* field studies of cloud physical properties and (3) the development of realistic 3-dimensional cloud ensemble models, with the objective of achieving vastly improved area-averaged representations of clouds and their effect on radiation transfer, atmospheric heating and the planetary radiation balance, suitable for incorporation in climate models (Section 4.3.2).

Surface hydrologic processes govern the partitioning of radiant energy between sensible and latent heat fluxes, thus controlling land surface temperature, evaporation and climate. Furthermore, the impact of weather and climate on water resources is governed by the partitioning of rainfall between evaporation, soil moisture and run-off. The partitioning is controlled by complex physical and biological land surface processes. Extensive observations of the relevant hydrologic properties are indispensable to characterize these processes on the global domain; NASA will combine the development of new experimental techniques for space-based measurement of basic hydrologic variables and properties, with a comprehensive program of field studies, data analysis and land surface process modeling and algorithm development (Section 4.3.3).

Investigating the relationships between large-scale climate and weather patterns must principally rely on numerical simulation with atmospheric circulation models (AGCM) that resolve weather systems, including relatively small-scale and severe weather phenomena (such as hurricanes and tornadoes). Essential for addressing these two objectives is the capability to acquire and analyze global atmospheric temperature, moisture, precipitation, and ocean surface wind data, the latter providing a direct measure of storm tracks, strength, and life cycle over the expanses of the ocean (Section 4.3.1). Another requirement is the capability to ingest and optimally assimilate a broad range of meteorological observations and derive reliable descriptions of both large-scale atmospheric climate and mesoscale storms (Section 4.3.4).

4.3.1 ATMOSPHERIC CIRCULATION DYNAMICS AND THERMODYNAMICS

Much of what we currently know or can infer about the general circulation of the atmosphere and the global energy and water cycle is derived from routine observations of basic meteorological variables: atmospheric pressure, temperature, moisture and wind. This information is obtained globally from a multiplicity of sources, notably *in situ* measurements by balloon-borne radiosondes and global remote sensing by operational meteorological satellites. A top scientific priority is to improve or develop space-based observing systems that can match the measurement quality now achieved only with dense *in situ* observing networks over limited regions. The NASA aims to develop advanced remote sensing systems and supporting scientific know-how, and to transfer these capabilities to operational observing programs, such as NPOESS, that can maintain observation continuity indefinitely in the future.

4.3.1.1 Systematic Global Atmospheric Measurements

Global Temperature and Water Vapor

Atmospheric temperature and moisture are the primary indicators of the state of the atmosphere. Consistent and accurate global temperature and moisture records are essential for identifying transient climatic variations and long-term trends, as well as more subtle changes such as variations in the vertical stratification or stability of the atmosphere. From an application perspective, global temperature and moisture are the primary state variables for initializing numerical weather prediction. Trace amounts of water vapor also play an important role in the chemistry of the stratosphere, in relation with stratospheric temperature and circulation; the corresponding scientific issues and NASA research strategy are discussed in Chapter 3.

The existing temperature and moisture "TIROS Operational Vertical Sounder" (TOVS) sensor system deployed on current polar operational environmental satellites is derived from original NASA instruments first flown on Nimbus-6 (1975) and TIROS-N (1978). A decisive breakthrough is expected with the Atmospheric Infra-Red Sounder (AIRS), which will be the first satellite sensor capable of emulating the accuracy of *in situ* temperature and moisture profile measurements. AIRS data will be available for the expected six-year lifetime of the EOS Aqua mission (2001-2006).

The long-term objective of NASA is to enable temperature and moisture measurements of quality similar to AIRS on operational environmental satellites. NASA is working with the NPOESS Integrated Program Office to promote this objective, and plans to participate in the development of a bridging mission for continued research-quality temperature and water vapor observation in the interim period between the termination of EOS Aqua and the first NPOESS mission. This NPOESS Preparatory Project (NPP) mission is described in Box 5. NASA recognizes that optimal exploitation of any satellite measurement requires sustained scientific investments, including validation and intercomparison studies, development of more accurate retrieval algorithms and re-processing of past data. NASA will continue to support research for validation and scientific exploitation of remote sensing data acquired by the NPP mission and following operational satellite systems.

NASA also intends to explore alternative measurement techniques, the most promising of which is based on precise determination of atmospheric refractivity profiles near the Earth limb from accurate measurements of the propagation delay of Global Positioning System (GPS) signals between any one member of the GPS constellation and satellite-borne receivers in low Earth orbit. GPS occultation measurement can provide accurate values of atmospheric density, pressure and temperature as a function of altitude with good vertical resolution but relatively modest horizontal resolution, from a height of about 30 km down to about 5 km. Because the absolute accuracy of GPS occultation measurements is limited only by the precision of atomic clocks, the technique is expected to provide a very consistent record of global atmospheric temperature, as needed to detect long-term trends. Further algorithm development and methodological studies will be needed to extract the full atmospheric information content of GPS occultation data, notably close to the Earth surface.

Box 5
NPOESS Preparatory Project (NPP)

From a NASA perspective, the NPP mission addresses the high-priority objective of maintaining the continuity of two critical EOS measurements in the post-2002 period. From the NPOESS perspective, the mission provides the opportunity to test in orbit two major new NPOESS sensor systems, as well as several innovative spacecraft technologies. The current plan is for a 5 year mission launched in 2005.

NPP embraces the objectives of the Global Terrestrial and Oceanic Productivity Mission (see Box 1) and will provide moderate-resolution multispectral imaging data across the visible and infrared spectrum, for a multiplicity of atmospheric, oceanic and land cover applications. This function will be provided by the Visible and Infrared Imaging Radiometer Suite (VIIRS) developed by the NPOESS program.

The NPP mission will also carry an advanced atmospheric sounder system, consisting of an infrared Fourier-transform spectroradiometer (Cross-track Infrared Sounder) developed by the NPOESS program, and an Advanced Technology Microwave Sounder developed by NASA. Altogether, the two sensors are expected to fulfill the EOS accuracy requirements for global atmospheric temperature and water vapor profiles measurements (1°C global RMS temperature accuracy in each 1km-layer of the troposphere).

In cooperation with several international partners, NASA is currently building an experimental constellation of five scientific satellites, each carrying a NASA-developed occultation GPS receiver. These international satellite missions of opportunity are Oerstedt (Denmark) and Sunsat (South Africa) launched in 1999, CHAMP (Germany) and SAC-C (Argentina) to be launched later in 1999, and GRACE (cooperative mission with Germany) to be launched in 2001. The next stage in the development of the radio-occultation technique may be a pre-operational constellation of dedicated satellites, proposed by an international consortium led in the USA by the University Corporation for Atmospheric Research, that would deliver GPS soundings in real-time for immediate assimilation in numerical weather prediction models.

Global Precipitation

Changes in the total amount and timing of precipitation directly affect runoff and the intensity of floods or droughts, as well as chemical processes in the air, biological processes on land and the oceanic circulation. Quantitative measurement of the time and space distribution of global precipitation is the next highest climate research priority after atmospheric temperature and moisture, and an essential requirement to understand the coupling among atmospheric climate, terrestrial ecosystems and water resources. Satellite remote sensing is the only means to acquire global rainfall data, considering the paucity of surface observations over the ocean and sparsely populated land areas.

Box 6
Global Precipitation Mission

The Global Precipitation Mission is meant to be a demonstration for a future operational global precipitation observing program combining passive and active microwave remote sensing techniques. The measurement methodology is based on frequent observations by a constellation of passive sensors, while detailed profile data will be provided by a common rain radar satellite for refinement and validation of retrieval algorithms for all spacecraft in the constellation. The observing system will consist of:

- A single "calibration" spacecraft carrying both an advanced rain radar and a multi-frequency microwave imaging radiometer.
- Two SSM/I sensors on operational DMSP satellites (to be replaced eventually by the multi-frequency Conical-scanning Microwave Imager-Sounder sensor on NPOESS),
- Four to six dedicated polar-orbiting spacecraft, each carrying identical or compatible microwave imaging radiometers, on staged orbits distributed so as to provide repeat observations at 3 hour intervals or less.

NASA will explore with international partners the means to implement such a multiple satellite system.

Precipitation information can be inferred from passive microwave imaging radiometer data acquired by existing operational environmental satellites (DMSP) and eventually NPOESS. Recent results from the Tropical Rainfall Measuring Mission (TRMM) show that the detailed cloud particle profile information provided by an active microwave sensor (Precipitation Radar) can be used effectively to improve the accuracy of rain rate estimates based on passive microwave measurements only. However, none of the existing or planned operational systems (nor *a fortiori* the single EOS Aqua mission) will provide sufficient sampling frequency globally (repeat interval of 3 hours or less) to capture the considerable spatial and temporal variability of precipitation events and provide a reliable estimate of total rainfall. NASA plans to seek the cooperation of international partners and deploy in the next five-to-ten years, an experimental satellite constellation that will achieve the required global coverage and sampling frequency for measuring global precipitation (See Box 6).

Global Tropospheric Winds

For over 20 years, researchers have been pursuing the development of Doppler lidar techniques for direct measurement of atmospheric winds in clear air. Direct observation of the global wind field would be extremely valuable for numerical weather prediction, as well as scientific diagnostics of large-scale atmospheric transport, weather systems, and boundary layer dynamics. Because of the lack of reliable, sufficiently dense, and accurate wind observations, uncertainties in model-derived estimates of divergent flow component of the global atmospheric circulation constitute a serious limitation in our understanding of the global energy cycle and the atmospheric transport of water, energy, and chemical species.

At present, however, the state of technology is such that a space-based Doppler lidar system could only deliver relatively sparse wind data, limited to air parcels where sufficient particulate matter tracers (aerosol or non-convective cloud) exist to produce a measurable backscatter signal. Such sparse wind vector measurements (even single component line-of-sight velocity data) could be assimilated by atmospheric general circulation models and would yield a significant incremental improvement in the quality of global analyses and numerical weather prediction, especially in the southern hemisphere and the tropics. On this account, the demonstration of Doppler lidar wind measurement from space could be a promising operational precursor mission. On the other hand, much technological progress leading to the development of more powerful, more energy-efficient and more reliable lasers is needed in order to realize the full potential of this active sounding technique for scientific research and applications.

Wind information can also be inferred from the motion of clouds (or patches of moist air) observed by geostationary satellites (see 4.3.1.3 below). Such measurements currently lack precision, especially in the assigned altitude level of the observed wind vectors but future high-resolution geostationary imager-sounder instruments may provide useful tropospheric wind profile information to follow, hour-by-hour the evolution of severe weather disturbances, notably hurricanes.

4.3.1.2 Global Air-Sea Fluxes

Knowledge of heat fluxes over the world ocean is essential in order to balance the global water and energy budgets. Accurate flux values can be derived from *in situ* measurements at a particular location or from an array of instruments such as may be deployed on the occasion of a major measurement campaigns at sea (e. g. TOGA-COARE). On the other hand, no existing surface- or space-based observing system can directly provide estimates of ocean basin-wide heat and water fluxes of sufficient accuracy for quantitative climate diagnostic study or prediction validation purposes. The most reliable global estimates of air-sea fluxes so far have been derived from operational global meteorological data assimilation and prediction products, using state-of-the-art atmospheric general circulation models. Such model products have reached the level of accuracy (residual uncertainty ~ 10 Watt/m^2) where meaningful heat and water budget closure experiments can be attempted over the area of an ocean basin.

Any additional observational information about the state of the atmosphere and the general circulation, that can serve to refine the knowledge of the "atmospheric demand" for water and heat, will contribute to inferring more accurate estimates of large-scale air-sea flux. NASA observing programs contribute unique data sets to advance toward this goal, notably the most accurate ocean surface wind velocity data so far (NSCAT; Seawinds), improved atmospheric temperature and humidity profiles data (AIRS/AMSU/HSB; ATMS); improved ocean surface temperature and total precipitable water measurements (MODIS; TRMM microwave imager; EOS Aqua/ASMR). NASA will support investigations aiming to improve the utilization of space-based and *in situ* measurements to derive and validate large-scale estimates of energy and water fluxes at the air-sea interface.

4.3.1.3 Mesoscale Weather Observation and Research

Quantitative precipitation forecast, using available *in situ* measurements and remote sensing data, is a principal scientific objective of the U.S. Weather Research Program (USWRP), as well as NASA's Earth system science program. Detailed diagnostic and model investigations of the structure and dynamics of mesoscale weather systems, as well as their relationship to the large-scale flow of the atmosphere, are needed for this purpose. Additionally, the scientific study of intense mesoscale weather systems (e. g. Hurricanes) and fast-developing severe weather phenomena (e. g. tornado-generating storms) is of paramount importance for weather forecasting and the protection of life and property, and a major scientific objective of the USWRP. In general, improved knowledge of the dynamics of convective cloud system will be needed in order to quantitatively assess vertical exchanges of momentum, heat and water that affect global climate, as well as atmospheric transport of chemical constituents through the troposphere.

Understanding the connections between global climate and weather is a central objective of this theme, requiring reliable characterization of mesoscale weather systems development, intensity and life cycle. So far, the most useful source of observational information for this purpose is the record of ocean surface wind data derived from space-based microwave scatterometer measurements (Seawinds) at a spatial resolution of 25km and wind accuracy of 2 m/s (see chapter 5: Ocean and Ice).

Geostationary Observing Systems

Field observation campaigns can provide comprehensive observations of the structure of individual mesoscale weather systems in a limited number of cases. Notwithstanding the value of such comprehensive data sets, continuous observation of a large atmospheric domain from geostationary platforms, such as the Geostationary Operational Environmental Satellites (GOES), offers a much faster means to determine the statistics of these scattered and short-life weather phenomena and constitute an essential tool for relating weather disturbances to large-scale circulation patterns. The NASA Instrument Incubator Program (technology development) and New Millennium Program (flight demonstration) have been tasked to improve upon the current remote sensing capabilities in geostationary or even more distant observing platforms. Two promising avenues for pioneering NASA contributions to weather system monitoring are:

- Observation of tropospheric temperature/moisture profiles, wind pattern and moisture inflow in the *far field* around weather systems, where the cloud cover is not solid. Such observations would be obtained from geostationary orbit by infrared atmospheric sounder instruments that could resolve the vertical structure of tropospheric water vapor.
- Diagnostics of convective cloud system development and life cycle, based on continuous observation of lightning flash rates, with special emphasis on tornado-generating storms and otherwise severe rain storms.

The first has been selected as the objective of the third New Millennium Earth observation technology demonstration mission (GIFTS). Successful development of this remote sensing capability can lead to more reliable prediction of fast developing severe weather phenomena. Considering the benefits of mitigating the heavy societal cost of severe weather events by extending the range of timely warning and the development cost of prototype instruments, application to operational environmental satellite systems is expected to follow.

Field Campaigns

The estimation of precipitation rates from active and passive microwave measurements is actually based on a cloud model simulation initialized with satellite observations of ice and liquid water in precipitating clouds. The validation of such rainfall estimation algorithms (or cloud system models) is based on model comparison with detailed field observations of cloud microphysical properties, cloud mesoscale structure, atmospheric temperature and moisture profiles.

The TRMM Ground Validation program, involving a series of high-flying aircraft campaigns over various tropical sites, is intended to obtain measurements similar to those provided by the satellite (at higher spatial resolution), in addition to *in situ* raingauge and surface-based meteorological radar observations. Data from TRMM ground validation case studies provide independent information on the total amount and vertical structure of precipitating water in convective and stratiform cloud systems, that can be directly compared to TRMM rain rate estimates. The field campaigns also provide the full range of measurements needed to refine and validate the TRMM retrieval algorithms. This effort is expected to continue, as appropriate, though the life of the TRMM mission and similar ground validation activities are expected to continue for a later Global Precipitation Mission.

In parallel, the investments made in the TRMM and similar ground validation program provide the means to carry out unique investigations of mesoscale cloud systems, notably tropical hurricanes. The Convection and Moisture Experiment (CAMEX) field study series, conducted by NASA in cooperation with the National Oceanic and Atmospheric Administration, collected observations of unequalled high-spatial and temporal resolution to characterize the 3-dimensional structure, motions and dynamics of successive Atlantic hurricanes during the 1998. The CAMEX program is thus emerging as a major scientific component of a multi-agency effort to observe tropical cyclone formation, motion and intensification, and improve the prediction of hurricane landfall. Study of hurricanes near landfall is a priority of the USWRP, a joint research effort of the US Navy, NASA, NOAA, NSF, and the academic research community. The overarching objective of the USWRP is to improve the accuracy and reliability of weather forecasts for high impact weather that can disrupt the functioning of society.

The program is expected to evolve toward dedicated field and model studies of critical weather systems over a full life cycle (principally by means of dedicated aircraft campaigns), including:

- Dynamical and microphysical processes in convective cloud systems associated with tropical storms, fronts, and monsoons, that can cause severe weather and flood,
- Model representation of precipitation processes in cloud-scale, mesoscale and global models.
- Impact of assimilating space-based observations of precipitation and associated properties on rainfall prediction skill in mid-latitude and tropical weather systems.

Field measurements will be complemented by the development of appropriate mesoscale atmospheric models (horizontal resolution on the order of 1-15km) and assimilation systems for model initialization using 3-dimensional air motion data, temperature and water vapor data, radar reflectivity and/or inferred microphysical properties, and surface rainfall. NASA will support an active program of field campaigns using unique NASA aircraft platforms and sensors, as a contribution to multi-agency studies of mesoscale weather processes.

4.3.2 CLOUDS AND RADIATION IN THE EARTH'S CLIMATE

The impact of clouds on the Earth energy balance is second only to that of water vapor. Clouds contribute half the planetary albedo, reflecting about 50 Watt/m^2 of incoming solar radiation back to space, while cloud absorption reduces by 20 Watt/m^2 the loss of terrestrial radiation to space (compared to 30 Watt/m^2 for all greenhouse gases other than water vapor). Even a modest error in predicted cloud cover could seriously impair model estimations of global climate change. It is generally recognized that clouds account for most of the remaining 1.5 - 4.5K uncertainty in model estimates of global warming that could result from a doubling of CO_2. The importance of this radiative effect justifies the high priority given to cloud-radiation feedback research by national and international scientific advisory bodies (notably the Intergovernmental Panel on Climate Change; IPCC, 1996). In addition to their impact on the planetary radiation balance, clouds govern radiative heating in the atmospheric column and radiation fluxes (especially solar radiation) reaching the Earth's surface.

Other particulate matter present in the atmosphere (aerosols) also has a distinct, albeit much smaller impact on the planetary radiation balance. The importance of aerosols in global climate change is related not so much to the absolute value of their contribution to the planetary radiation budget, but rather to changes that can be traced to anthropogenic sources. Accordingly, discussions of the diverse science issues arising with aerosols are grouped in Chapter 3, together with other climate forcing factors. (See section 3.3.2). On the other hand, aerosols also act as cloud condensation nuclei and may modify the optical properties of clouds: this indirect radiative forcing effect intimately involves cloud system dynamics and is considered part of cloud process research (Section 4.3.2.2).

4.3.2.1 Planetary Radiation Budget and Global Cloud Measurements

Considerable progress has been achieved by the NASA-sponsored Earth Radiation Budget Experiment (ERBE) since its launch 1984. ERBE measurements of broad-band radiation fluxes at the top-of-the-atmosphere (TOA) constituted the first major advance toward quantifying the radiative effects of clouds on a planetary scale and provided a very useful constrain on radiation transfer computations in climate models. Similar information, albeit with considerably lesser accuracy but more spatial and temporal detail, has been derived for the last 15 years from narrow-band visible and infrared radiometer data on polar-orbiting and geostationary operational meteorological satellites, as part of the International Satellite Cloud Climatology Project (ISCCP) organized by the World Climate Research Program, with contributions from NASA and other satellite operating agencies. The ISCCP collects and analyzes satellite radiance measurements for cloud system classification, estimation of cloud optical properties, and determination of diurnal, seasonal and interannual variations. Both data sets have been effectively used to improve the representation of clouds in climate models and understand their relationships to weather systems (ISCCP) and climatic variations (ERBE).

Several significant scientific problems remain to be addressed, notably the need for improved knowledge of the angular distribution of reflected solar radiation (needed in order to estimate total radiant energy fluxes on the basis of radiance measurements in one direction only). In this regard, major advances are expected from a series of advanced broadband radiometer instruments (CERES) on the Tropical Rainfall Measuring Mission (TRMM) and first two major EOS missions, leading to much reduced uncertainty on the terms of the planetary radiation balance (on order of 1 Watt/m^2). Additional supporting information will also be obtained from two Moderate-Resolution Imaging Spectro-radiometers (MODIS) on EOS Terra and Aqua (fractional cloud cover and cloud top optical properties), the Multi-angle Imaging Spectro-radiometer (MISR) on Terra (viewing angle diversity), and the Advanced Infrared Sounder (AIRS) on EOS Aqua (resolution of the infrared spectrum and correction on limb-darkening effects). Altogether, it is anticipated that major progress will be made during the next five years in determining the terms of the planetary radiation balance at the top of the atmosphere, thereby providing a definitive reference point for global climate model simulations.

In the long term, the extent to which continued broadband radiation flux measurements will yield further advances in the understanding of climate dynamics and radiative transfer in the Earth atmosphere is the subject of scientific discussion. Under any circumstance, the NPOESS program is planning to continue systematic broadband radiation measurements with CERES or a similar instrument on one of the two NPOESS spacecraft indefinitely in the future. Possibilities for flying a spare CERES instrument in order to maintain a continuous record through the interim period between EOS and NPOESS are being considered by NASA.

In addition, NASA will continue a strong research and data analysis program to extract the information contained in the wealth of narrow-band radiance measurements available from US and international observing systems. This may include radiance data processing and re-processing projects (such as ISCCP and the surface radiation budget climatology project) that provide valuable cloud diagnostics and derived radiation flux information, and support centers of scientific excellence in cloud and atmospheric radiation research.

4.3.2.2 Cloud, Aerosol and Radiation Process Research

The optical properties of clouds and aerosol are complex functions of number density, particle size and shape, physical state (liquid water or ice) and chemical composition in the case of aerosols. The impact of clouds on atmospheric radiation transfer and radiation flux divergence (radiative heating) depend strongly upon the 3-dimensional structure of cloud systems. Likewise, the radiative forcing caused by aerosols depends upon masking by clouds and the underlying surface albedo. In addition, significant indirect radiative forcing effect may be induced by certain classes of aerosol that act as cloud condensation nuclei. The presence of a higher density of condensation nuclei results in the formation of a larger number of smaller droplets, with longer residence time and enhanced optical depth for a given amount of liquid water. The duration of this cloud seeding effect on an evolving population of cloud droplets of increasing age and changing properties is not known. The connections between cloud microphysical processes and radiative properties are obviously quite complex and largely unexplored.

All currently existing measurements suffer from a common bias, inherent to the observation of radiances emerging from cloud tops. The parameters of most direct scientific interest – atmospheric heating and surface radiation fluxes – cannot be determined unambiguously from TOA radiance measurements, because different cloud layering within an atmospheric column may yield the same outgoing radiation flux at TOA (but very different surface fluxes). Thus, the scientific challenge in cloud and atmospheric radiation research is probing the vertical distribution and optical properties of cloud particles in the atmospheric column, in order to provide measurement-based estimates of radiation flux divergence instead of relying on climatological statistics or models. This is made possible by the emergence of active sounding sensors that can probe the vertical structure of the cloudy atmosphere.

Cloud, Aerosol and Radiation Research Satellite Missions

The highest emerging research priority identified by the radiation science community is to acquire globally sampled, vertically resolved observations of cloud particle density, physical nature (ice or liquid water) and optical properties, and to relate these properties to the weather systems that generated the clouds.

NASA is planning two Earth System Science Pathfinder missions that are specifically designed to address this problem through active profiling of cloud and aerosol particles in the atmosphere:

- PICASSO-CENA mission, a US/French satellite project to observe the lowest range of optical depths (aerosols and optically thin clouds) by means of a two-frequency backscatter lidar sensor and a high-resolution solar radiation (oxygen A-band) spectrometer.
- Cloudsat mission, undertaken with the support of the US Air Force and the Canadian Space Agency. Cloudsat will investigate the intermediate range of cloud thickness (non-precipitating stratiform clouds and light drizzle) by means of a millimeter-wave Cloud Profiling Radar and a similar A-band spectrometer. Heavy precipitating clouds are already being observed, up to 40° latitude, by the TRMM Precipitation Radar.

Considering the time and space variability of atmospheric water vapor and clouds, and non-linear relationships between these factors and radiation transfer, simultaneous observations in the same air column are required. The PICASSO-CENA and Cloudsat missions will be launched simultaneously in 2003 and fly in formation with the EOS Aqua spacecraft. This three-spacecraft observing system will achieve a major advance in the ability to observe radiation fluxes, the three-dimensional structure of aerosol layers and cloud systems (including sub-visible cirrus cloud layers), and to infer radiative heating in the atmosphere and at the surface. With this breakthrough in the global observation of cloud optical properties and distribution, considerable improvement is expected, during the next 5 years, in the ability to understand, quantify and model the radiative impact of clouds on climate and their relationship to weather disturbances.

On the other hand, detailed simultaneous observation of cloud condensation nuclei (aerosols) and cloud particle density, size and properties, which would be needed to determine the indirect effect of aerosols on cloud radiative properties and climate, are still beyond reach. This is a scientific challenge that can only be approached indirectly through modeling of cloud microphysical processes.

Field Campaigns and In Situ Measurements

One of the largest gaps in our understanding of cloud/radiation processes concerns extensive tropical cirrus clouds, their development, persistence and their ubiquitous effect on regional and global radiation budgets. High-altitude tropical cirrus systems, which dominate cloud radiative forcing in the tropics, result from the vertical transport of water by deep convective cloud clusters. The process produces a wide variety of upper-level clouds, ranging from thick precipitating anvil clouds and medium-thick (non-precipitating) clouds, to thinner cirrus that are a widespread feature of the tropics. Each of these cloud types exerts a different influence on the radiation budget and thus the climate response. Building on the heritage of the FIRE (First ISCCP Regional Experiment) and SUCCESS (Sub-Sonic Contrail and Cloud Effects Special Study) field campaigns, the Cirrus Regional Study of Tropical Anvils and Layers (CRYSTAL) program will address this gap in our understanding.

CRYSTAL consists of three coordinated components: an intensive field campaign (2001), a cloud modeling program and data analysis studies. CRYSTAL principally address two scientific questions:

- Upper tropospheric distribution of ice particles and water vapor and associated radiation fluxes on storm and cloud system scales.
- Upper tropospheric cloud generation, re-generation, and dissipation mechanisms, and their representation in both regional-scale and global climate models.

Intensive field studies, involving the coordinated use of multiple aircraft platforms, surface, and satellite measurements, are an essential component of the cloud/radiation research strategy and the validation of forthcoming EOS measurements (CERES, MODIS and MISR) and relevant Earth System Science Pathfinder missions.

Cloud, Precipitation and Radiation Transfer Models

Accurate representation of cloud-climate feedback in climate models is indispensable for predicting the possible consequences of human-induced environmental changes. Such feedback mechanisms cannot be directly observed; rather they must be diagnosed from global observations of energy and water exchanges within the climate system, and climate model studies that relate flux variations to specific processes. On account of expected improvements in observing and data processing systems, the research strategy will rely on a hierarchy of models, ranging from cloud process-resolving models to general circulation models.

Microphysical models address the formation and growth of cloud particles in a saturated-vapor environment produced by atmospheric motions, including the roles of aerosols as condensation nuclei and of cloud particle freezing-melting processes. More work is needed to study the role of aerosols and the nature of aerosol processes in high altitude or polar ice clouds, and in mixed-phase situations. *Dynamical models* are used to investigate cloud particle growth and subsequent fallout, and their evaporation below cloud-level or the generation of rainfall. *Radiation transfer models* are the primary tool to study the effect of clouds on the radiative heating of the surface and atmosphere.

The ultimate objective is to develop and exploit comprehensive *Process-Resolving Cloud System Models* that explicitly represent the fundamental microphysical processes (such as the indirect effect of aerosols on cloud particle growth and radiative properties), as well as precipitation generated by the cloud. Such models can be compared directly to single-column parametric formulations of cloud processes in climate models. It is envisioned that cloud-resolving models will first be verified by comparison with detailed field measurements in various meteorological situations, and then compared with mesoscale models that reproduce the same meteorological fields. Finally, global satellite observations will be used to identify ensembles of similar cloud systems that can serve as a basis for generalizing results from individual case studies to climate statistics, and for validating the simplified representations of cloud processes in atmospheric general circulation models and climate models.

4.3.3 LAND SURFACE PROCESSES AND HYDROLOGY

The hydrological element in the Global Water and Energy Cycle research theme aims to understand the role of the terrestrial hydrosphere (and biosphere) in the Earth climate system. Surface hydrological processes influence weather and climate locally at all time scales, and large errors in surface temperature forecasts can be traced to poor handling of latent heat exchanges associated with evaporation, soil freezing or thawing. Land surface processes also influence summer precipitation over large regions in the interior of continents. Likewise, snow and frozen ground in late spring appears to have a lasting affect on weather patterns and, at high latitudes, the CO_2 intake of the boreal forest. In this manner, land hydrological processes may induce positive climate feedback that could enhance extremes of drought, or heavy precipitation and flood.

Equally significant is the governing role of land hydrological processes in the partitioning of rain water and snowmelt among evaporation, ground storage, and run-off to the river system. Understanding and modeling these processes reliably is a prerequisite for quantitative application of climate predictions to water resource management. In general, water transport and land-atmosphere-ocean teleconnections are not well understood. The principal obstacles hampering progress are insufficient large-scale observations, poorly resolved representations of hydrological processes in climate models, and the lack of comprehensive data sets for use in validating model formulations. NASA plans to address these deficiencies through better utilization of currently available land surface data, process model development and verification with intensive field measurements and aircraft observations, and large-scale diagnostic studies based (mainly) on satellite observations.

4.3.3.1 Experimental Land Hydrology Observing Missions

It is recognized that scientific questions regarding the role of terrestrial hydrology in the climate system cannot be answered on the basis of *in situ* measurement alone - the historical record is too short and the required observations are too extensive and impractical from a logistical standpoint. Effective use of remote sensing data is crucial to make progress in global water cycle research. It is a fact, however, that soil properties and soil water processes remain largely shielded from remote sensing based on the detection of electromagnetic signals, as the penetration depth of microwave radiation in wet soil is only a few centimeters. NASA recognizes these technical difficulties and gives high scientific priority to developing the means for global measurement of essential hydrological quantities from space, principally precipitation and near-surface soil moisture. In combination with additionally proposed experimental measurements of snow, soil freezing/thawing and rivers or lake stage, the possibility exists to estimate all components of the terrestrial water budget at regional to continental scales directly from observations.

Global Precipitation Mission

Knowledge of precipitation at the time and space scales of storms (about ten kilometers and one to several hours) is essential for understanding the impact of weather on land surface hydrology. Considerable progress in understanding the dynamics of precipitating systems is also needed for quantitative precipitation forecasting and climate prediction. Satellite-based remote sensing offers the only practical option for acquiring globally consistent precipitation data sets needed to test and improve weather and climate models, and to drive large-scale hydrological models that can infer surface moisture, ground water storage and run-off over the global land surface (see Box 4).

Soil Moisture Research Mission

At present soil moisture is the only primary hydrologic variable that cannot be measured at large spatial scale. Scientific evidence shows that soil moisture is the most significant indicator of the state of the terrestrial hydrologic system, and is the governing parameter for partitioning rain water among evaporation, infiltration, runoff. Soil moisture also plays a critical role in vegetative processes and provides the critical link between the physical climate system (water and energy) and biogeochemical cycles. Recent research has demonstrated that knowledge of soil moisture enhances predictability of summertime precipitation over much of the U.S.

The unresolved problems in measuring soil moisture from space are obtaining useful signals under a substantial vegetation canopy and reaching a useful depth within the uppermost soil layer while, at the same time, achieving useful spatial resolution (on the order 10-30 kilometers) and temporal sampling (repeat intervals of 1 to 3 days). Large real or synthetic apertures are required to meet these requirements in the low-frequency range of the microwave spectrum. Several alternative techniques will be studied by NASA for remote sensing of soil moisture from space, including 2-dimensional aperture synthesis adopted by the European Space Agency for a Soil Moisture and Ocean Salinity (SMOS) Earth Explorer mission planned to be launched in 2004.

Another potentially promising measurement concept is the gravimetric determination of changes in soil water storage, based on extremely precise observation of time-dependent changes in the Earth gravity field. The experimental GRACE gravity mapping mission will explore the extent to which this concept is applicable to land hydrology.

Cold Climate Land-Surface Process Research Mission

Cold season processes (snow extent and water equivalent, soil freezing and thawing) strongly affect the short-term hydrologic dynamics on the scale of river basins, and land-atmosphere feedback at continental scales. In the interior of North America and Eurasia, and in high altitude mountain areas, much of the annual precipitation contributing to streamflow occurs as snow during the winter months, with evident effects on the seasonal cycle of runoff. The freeze/thaw status of the soil surface determines the relative amounts of snowmelt and precipitation that contribute to runoff versus infiltration; differences in albedo between snow-covered and snow-free areas result in large changes in net radiation during the thaw period. While these processes are understood at local-to-catchment scales, available observations are inadequate to quantify the role of snow and frozen ground in the physical climate system. Research under NASA’s Boreal Ecosystem-Atmosphere Study (BOREAS) has shown that the onset of springtime thaw significantly influences the annual uptake of carbon by boreal forests, demonstrating the importance of observing the freeze-thaw transition to understand the interacting water, energy and carbon cycles at high latitudes.

Surface Water Level Monitoring Mission

Although river stage height can be conveniently observed *in situ* for small to moderate streams, the discharge of many of the world’s major rivers is not currently being monitored, or the data are not available to the scientific community. River discharge and changes in inland lake levels are integrators of runoff; the measurement of these basic hydrologic variables in near real-time would be an invaluable aid in validating climate and water resource predictions. River discharge is also an important driver of ocean circulation. Knowledge of changes in water storage by inland water bodies and their impact on regional and continental water budgets is also deficient due to a lack of observations. A number of tests, carried out with the Topex/Poseidon radar altimeter, demonstrated the ability to monitor level changes in large rivers and inland water bodies. Precision radar altimeters, currently being developed for oceanographic or polar research purposes are potentially capable of detecting very small changes (on the order of a few centimeters) in the stage of inland water bodies, but cannot provide the required short sampling interval

(1 to 3 days). The potential also exists for Doppler lidar measurement of river surface velocity and, in combination with river stage data, direct estimation of river discharge from satellite measurements.

4.3.3.2 Land Surface Process Studies and Field Campaigns

NASA has a long history of supporting hydrological field experiments, from the seminal HAPEX study in France to HAPEX-Sahel in sub-saharan Africa, FIFE in the Central Plains, and BOREAS in the Arctic forest. These intensive field studies serve three main purposes: (1) improvement of hydrologic process parameterization in mesoscale and general circulation models; (2) development and testing of remote sensing instruments and algorithms; and (3) development of procedures for assimilation of remote sensing data by process-resolving models. Currently, hydrological and joint atmospheric-hydrologic field studies, involving intensive *in situ* measurements and airborne remote sensing, constitute a very productive element of the NASA hydrology research program.

As part of a broader science strategy to understand the water and energy cycle at regional and continental scales, NASA also participates in more ambitious continental-scale experimental projects, which encompass the Mississippi river basin (GEWEX International Continent-scale Project) in the USA and the Amazon river basin in Brazil (Large-scale Biosphere-Atmosphere experiment). These continental-scale projects provide a research framework to test scaling process parameterizations and remote sensing algorithms developed from NASA field-scale experiments. These continental experiments, when combined with long-term data sets, should provide increased understanding of the mean state and variability of the water and energy budget terms at regional scales, thus providing a foundation for global analyses. NASA will continue to support fundamental process studies based on intensive *in situ* and aircraft observation, as appropriate, and will invest in an active program of field campaigns to test new remote sensing methodologies and instruments, in preparation for future experimental satellite missions.

4.3.3.3 Large-scale Hydrologic Diagnostic Studies and Modeling

Another important thrust is a program of large-scale diagnostic studies, based on existing global data sets, to investigate the seasonal, annual and interannual variability of water and energy cycles at continental-to-global scales. This effort addresses the central objective of the international GEWEX program and is the focus of EOS research on terrestrial hydrology. This research approach is particularly relevant for enhancing the reliability of streamflow predictions and related hydrologic forecasts on time-scales of hours to seasons, thus providing possibilities for transferring knowledge from research projects to water supply, flood control, and drought management applications.

Global and continental scale diagnostic studies are an effective means for integrating available measurements, physical understanding and model products covering many space and time scales. They address issues such as the impact of local and remote forcing on the terrestrial hydrological cycle, feedback to the atmosphere through changes in surface soil moisture, or the role of snow cover in modulating weather on seasonal time scales. A specific objective is exploring the connections between synoptic-scale atmospheric phenomena and small-scale hydrologic processes, developed through site-specific field experiments such as FIFE and BOREAS. Diagnostic studies also constitute a good basis for improvement of data assimilation algorithms, evaluation of data assimilation products (especially in data sparse regions), and advances in hydrologic prediction and water resources management.

Satellite data that have been used for large-scale studies include long-term records of atmospheric temperature and moisture, vegetation, temperature, and precipitation (e. g. SSM/I Pathfinder data reprocessing projects; Global Precipitation Climatology Project). An example of a global diagnostic approach is the GEWEX Global Soil Wetness study organized by the International Satellite Land-Surface Climatology Project (ISLSCP), with the support of NASA and several environmental research agencies. New developments in remote sensing algorithms from the TRMM and EOS programs are expected to yield major advances in the derivation of the basic data sets (precipitation, net surface radiation, near-surface humidity and air temperature) used for these and future more ambitious diagnostic studies, which include:

- Development of hydrologic models which can link hydrological processes across all scales. Application at large spatial scales requires the estimation of model parameters related to land surface characteristics (vegetation, soil, topography) based on remote sensing data, such as vegetation classification, vegetation indices, topography and soil types.
- Evaluation of the ability of hydrologic models to reproduce the observed natural variability, and the sensitivity of model outputs to modeling assumptions. The GEWEX Project for Inter-comparison of Land-surface Parameterization Schemes (PILPS) is an example of a current study in this domain. Diverse climate regimes need to be studied to gain confidence in model-derived water and energy budget information.
- Application of hydrologic models to assess the impact of improved land surface process formulations on hydrologic forecasting, weather prediction and water resources management.

4.3.4 ATMOSPHERIC DATA ASSIMILATION AND MODELING

The analysis of large data streams derived from global observation of the Earth from space is a principal concern of NASA. Four-dimensional data assimilation, using a time-dependent model of the atmospheric circulation, is the principal tool for integrating observations from different sources and producing a coherent picture of Earth system dynamics (circulation), thermodynamics (energy fluxes), hydrology (water fluxes) and biogeochemistry (ozone, carbon dioxide, etc.). In general, space observation offers unequaled global and uniform coverage, but only incomplete information about the phenomena under study. Combining remote sensing observations and *in situ* measurements, in a manner consistent with the dynamical, physical and chemical relationships that govern the system, is a powerful means of extracting the full information content of the observations.

Data Assimilation as an Operational Analysis Tool

Four-Dimensional Data Assimilation (4DDA) optimally combines diverse and incomplete observations with short term forecasts from a geophysical model to produce a succession of snapshots, each forming the best possible analysis of the state of the system under observation. The primary role of 4DDA is to deliver estimates of the relevant geophysical or chemical variables in the form of complete gridded fields as "data products" that can be used for a variety of scientific applications, from diagnostic studies of global Earth system processes to ancillary information for remote sensing retrievals. The assimilation model maintains dynamical, physical, and chemical consistency of the primary prognostic variables, produces internally consistent estimates of diagnostic quantities such as heating rates, surface fluxes and vertical motion that cannot be measured directly, and provides a means to assess the quality of observational data.

The reanalyses of past meteorological data conducted by three major center – the European Center for Medium-range Weather Forecasts, the NOAA National Centers for Environmental Prediction (NCEP) and the NASA Data Assimilation Office (DAO) - have provided an indication of the potential applications of 4DDA to climate research. The weaknesses as well as strengths of current 4DDA products largely reflect the past priorities of numerical weather prediction. The strengths lie in the representation of the mass and wind fields which most directly impact short and medium range weather forecasts, while the weaknesses are found in the representation of the hydrological cycle and in the vertical component of the tropical circulation. Currently, residual biases in estimated net surface energy and water fluxes are too large to reliably derive oceanic transport of heat and fresh water. Estimates of precipitation minus evaporation over land show significant discrepancies with independent river discharge measurements. Reducing systematic errors to a level that allows using data assimilation products directly for climatological applications constitutes the principal challenge to the DAO and associated researchers.

NASA will continue to invest in the operation and improvement of the system implemented by the DAO with the objective to match and improve upon the international state-of-the-art in extracting maximum information from satellite observation. The short-term objective is to implement a higher resolution version of the current assimilation system (global 1°x 1° grid) that realistically resolves meteorological fronts and other dynamically significant small-scale features of the atmospheric circulation. Next steps include the testing and implementation of a new dynamical core model developed in collaboration with the National Center for Atmospheric Research. The new model will use a modern (semi-lagrangian) advection algorithm that conserves flux quantities and provides an order-of-magnitude acceleration in computing speed over the current system. The model is also designed to allow convenient interchange of physical parameterization schemes with those developed by the climate modeling community. NASA encourages and will support the development of such cooperation with the academic community and partner agencies, particularly NOAA/NCEP.

Data Assimilation as a Learning Tool

As highlighted in the National Research Council report on *Four-dimensional Model Assimilation of Data* (1991), data assimilation is also "a systematic, structured, and open-ended learning process". By continually confronting the geophysical model with observations, 4DDA quantifies the mismatch between observations and model forecasts, and provides clues for further model improvements. This interactive optimization of model and data analysis is perhaps the single most important benefit of data assimilation in a research mode. This linkage has been successfully exploited by Numerical Weather Prediction centers to improve short term weather forecasts. The challenge for the broader Earth science community is to build upon this success by extending the application of assimilation systems to all relevant components of the Earth system, and developing 4DDA methodologies capable of exploiting non-standard measurements (especially new space-based observations).

In this perspective, the NASA global data assimilation program will be the principal means for integrating knowledge gained about the physics of individual atmospheric and hydrologic processes into a coherent dynamical representation of the global climate system and, eventually, the full Earth system. Each improvement in the formulation of 4DDA model dynamics and physics is a step toward quantitative understanding of the climate system and its response to external forcing. NASA will encourage closer interaction between discipline-oriented process research (theoretical studies, field campaigns, and process-resolving models) and global data assimilation activities across the range of geophysical and chemical variables measured routinely by operational and research observing systems. In particular, NASA will encourage diagnostic analysis of global data assimilation products and direct comparison of deterministic (short-term) predictions with observations of specific weather phenomena at the same location and time.

Assessment of Weather System Predictability

The ability to derive useful predictions of regional climate fluctuations is limited ultimately by the ability to effectively forecast probable impacts on regional scales. Systematic data assimilation and experimental ensemble predictions of the atmospheric circulation (in a delayed mode, using observed surface boundary conditions) constitute the ideal means to test the statistical significance of linkages between global climate variations and changes in regional weather patterns and hydrologic regimes. The latter objective has yet to be addressed by DAO and constitutes a major scientific challenge in the coming five years, with a potential for scientific findings and practical applications commensurate with NASA's resource investment. Scientific collaboration with operational weather prediction centers will be especially favored in the pursuit of this scientific goal.

Technical Challenges

A key requirement for effectiveness of 4DDA systems in climate and global change studies is the ability to resolve all significant scales of motion in the atmospheric circulation. This requirement implies quite high spatial resolution and makes 4DDA techniques very computer intensive. The 1991 NRC report suggested that global assimilation systems should have 100 km or better horizontal resolution with about 30 levels in the vertical dimension, in order to resolve important boundary layer and stratospheric phenomena. Current global assimilation systems meet or exceed these specifications; mesoscale models with even higher spatial resolution have been developed for realistic simulation of convective and stratiform cloud ensembles. Both kinds of numerical simulation stress existing computing capabilities.

In general, the demand for computing resources for such cutting-edge numerical tasks cannot be met by the acquisition of faster and more powerful computer equipment alone. A major investment is needed in numerical analysis, algorithm development and software optimization. Transition to more efficient numerical codes, even at the expense of programming convenience for scientists, is a necessary evolution that will be required of any world-class modeling and data assimilation center. It is the intent of NASA to promote the necessary investments in advanced software and numerical code optimization for data assimilation models and climate models alike. In order to accelerate the pace of development, expanded cooperation will be sought with academic institutions, government laboratories, and operational weather prediction centers.

Scientific Challenges

The principal current scientific challenge involved in atmospheric circulation modeling is the development of parametric formulations of unresolved small-scale processes that are consistent with higher model resolution. In general, more detailed, physically realistic, and also more complex "parameterization" schemes are required to match the higher spatial resolution of the basic dynamical model. Progress in this domain will depend upon advances in process observation and process-resolving models, as well as the vigilance of atmospheric circulation and climate modeling groups for exploiting the latest advances for the improvement of process parameterization (see section 3.3.4.1). Of particular importance in the next few years will be Cloud Ensemble Models that allow explicit representation of small-scale dynamics and microphysics, with emphasis on realistic simulation of precipitating cloud systems.

4.4 LINKAGES

Linkages with other NASA programs

The principal scientific linkages of the Global Water and Energy Cycle research theme within the NASA program are with Earth System and Observation and Modeling (Chapter 7). The GWEC component of the NASA Earth Science program provides improved physical understanding and modeling (parameterization) of atmospheric and hydrologic processes in the context of global climate studies, and also provides essential observing programs and products for climate diagnostic studies. Important linkages also exist with the Atmospheric Chemistry program, concerning the atmospheric transport and mixing of chemical species and the indirect effects of aerosol on cloud optical properties, precipitation and radiation transfer (Chapter 3). The connection with the Ecosystem Biology and Biogeochemistry program lies principally in the two-way interaction of terrestrial ecosystems and land hydrologic processes (Chapter 2). In addition, NASA supports research on the impact of Climate on Health through the provision of relevant global observational data sets and analyses products.

Linkages with other US agencies (Global Change Research Program)

The NASA Global Water and Energy Cycle research program has very active connections with at least three partner agencies within the US Global Change Research Program. NASA and the National Science Foundation (NSF) cooperate in a number of investigations focused on the study of physical atmospheric processes, especially the development of cloud process-resolving models (also known as Cloud Ensemble Models) and atmospheric general circulation models. The latter effort is led by the NASA Data Assimilation Office and the National Center for Atmospheric Research.

NASA interacts with the National Oceanic and Atmospheric Administration (NOAA) at a multiplicity of levels. On the technical level, NASA has historically been at the origin of most instruments used in NOAA's operational polar-orbiting or geostationary environmental satellite programs. Currently NASA discharges program management responsibility for the acquisition of operational environmental satellites on behalf of NOAA. The decision to merge the operational polar-orbiting meteorological satellite programs of NOAA and DOD has altered this historical relationship but NASA is engaged in the development of advanced instrument technologies that will be infused in the emerging National Polar-orbiting Environmental Satellite System (see Box 3).

NASA and NOAA also cooperate in a wide variety of research projects. NASA brings unique global observation tools and airborne observing assets to the NOAA-led U.S. Weather Research Program and the NASA Data Assimilation Office cooperates with NOAA's National Centers for Environmental Prediction in addressing the quantitative rainfall prediction research objective of that Program. NASA and the NOAA Office of Global Programs and NASA also co-sponsor the GEWEX Continental-scale International Project over the Mississippi river basin.

Finally, NASA is a major scientific partner of the Department of Energy Atmospheric Radiation Measurement Program through joint fundamental studies, cooperative instrument calibration activities, and field measurement campaigns involving NASA's airborne remote sensing facilities.

International linkages

The NASA Global Water and Energy Cycle program component is closely aligned with the scientific goals and scientific strategy of the Global Energy and Water Cycle Experiment (GEWEX) program of the World Climate Research Program, and the Biospheric Aspects of the Hydrological Cycle project of the International Geosphere-Biosphere Program. Historically, NASA played a leading role in the development of GEWEX and still relies on this international program to nurture cooperative relationships with the worldwide atmospheric science community. NASA is a major partner in most GEWEX projects, from the International Satellite Cloud Climatology Project, initiated in 1982, to the Global Water Vapor Project undertaken in 1999.

Several major bilateral cooperative programs or projects have also been developed by NASA with foreign agency partners, notably Japan (joint implementation of the Tropical Rainfall Measuring Mission and a future Global Precipitation Mission; realization of the Advanced Microwave Scanning Radiometer on EOS Aqua), France (joint realization of the PICASSO-CENA Earth System Science Pathfinder mission) and Canada (participation in the Cloudsat Earth System Science Pathfinder mission).

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CHAPTER 5

OCEAN AND ICE IN THE EARTH SYSTEM

5.0 INTRODUCTION

The Earth's oceans and ice masses affect many facets of human life from the viability of coastal communities and ocean trade to climate conditions well within the interior of continents. During the last two centuries, mountain glaciers have been retreating in alpine valleys, sea level has risen by tens of centimeters and global-mean surface temperature has warmed substantially (the latter trend resuming in the early 1970's after a thirty year pause). In recent years, two of the largest El Niño events of the century have caused considerable disruptions and have been the focus of much public attention. Climate, including the ocean and ice environments, is no longer perceived as a static property of the environment, but is now viewed as having a dynamic state that is expected to evolve in the future.

Climate changes that occur over periods of years, decades or longer combine natural variability with the Earth system's response to changes in external forcings such as radiation from the Sun and, in recent times, disturbances by human activities, e. g. the increasing concentration of carbon dioxide in the atmosphere. The dynamics of the ocean circulation play a crucial role in natural climatic variability and, given appropriate initial values of the relevant oceanic variables, recent scientific advances have enabled predictions of shorter-period climate variations, such as the El Niño/Southern Oscillation phenomenon, that result from interactions of the oceans with the global atmosphere.

The Global Ocean and Ice research theme focuses on the dynamics of the slower components of the physical climate system, namely the ocean circulation and the mass balance of polar ice sheets. These components respond to disturbances with much greater inertia – longer "memories" – than the atmosphere, and therefore damp out fast changes (e. g. the seasonal cycle) and govern the pace of longer period climate variations. Because of the large mass and heat capacity of the ocean, the relatively slow oceanic circulation is responsible for approximately half the global equator-to-pole meridional heat transport. Ice sheets are expected to change on even longer time-scales, centuries to millennia. Nonetheless, recent discoveries point to the possibility of significant changes on much shorter periods.

Both the ocean circulation and the mass balance of large ice bodies are driven by conditions at their boundaries. The former strongly interacts with the atmosphere through exchanges of momentum, energy (heat), water, and other chemical substances. The ice sheets currently also play a dynamic role in the climate system; they create special atmospheric conditions locally (e. g. katabatic winds in Antarctica) and discharge large icebergs that influence the fresh water balance of the ocean. Polar ice sheets and other ice bodies constitute by far the largest fresh water reservoir on the planet. Even fractional melting of these ice sheets could cause very substantial rise in global sea level in the future, as has occurred in the past.

Because of strong ocean-atmosphere-ice interactions, it is not strictly legitimate to consider the dynamics of either component independently from the other on climatic time scales. Nevertheless, much remains to be learned by studying the responses of oceans and ice sheets to (observed or computed) surface forcing by the atmosphere. Such is the research paradigm followed in this chapter. The dynamics of the coupled ocean-atmosphere-land-ice system are considered in chapter 7 on Earth System Observations and Modeling, while the detailed studies of the "fast" atmospheric and hydrologic processes that occur in the atmosphere, in the atmospheric boundary layer and at the land surface are discussed in chapter 4 on Global Water and Energy Cycle research.

5.1 MAIN SCIENCE QUESTIONS

- ***How is the global ocean circulation varying on climatic time scales?***

The circulations of the Earth's oceans and the global atmosphere provide the mechanism by which the excess energy received from the Sun in the tropics is redistributed to the whole planet. Heat transport by the oceans amounts to about half the cycling of heat from equator to pole. The oceanic circulation also controls the supply of nutrients that feeds marine productivity and modulates the global biogeochemical cycles (notably, the carbon cycle). Any significant change in the oceanic circulation that results in variations of ocean surface temperature patterns has an immediate impact on atmospheric winds, weather and climate. The best known among these variations are the transient changes associated with El Niño/Southern Oscillation (ENSO) phenomena; the existence of other modes of variability is surmised, but establishing the statistical robustness of such preferred modes, characterizing the mechanism that may cause them, let alone predicting their future evolution and their impact on climate, are major scientific challenges. A record of variations in the global ocean circulation is an essential information basis to address this problem.

- ***Will climate variations induce major changes in the deep ocean?***

The deep ocean circulation and the rate of formation of "deep water" that sinks to intermediate or bottom depths have profound implications on the long-term storage of excess heat and chemicals in the ocean's depths; the recycling of nutrients; marine productivity and the carbon cycle; and the long-distance transport of heat from one ocean basin to the other. There is theoretical (modeling) evidence that the overturning circulation of the Atlantic ocean could be very sensitive to freshening of surface waters; compelling paleoclimatic evidence exists that Atlantic deep water formation was drastically reduced during certain periods in the past, notably during the recovery from the last glacial episode. A potential transition from the current overturning circulation to a regime where deep water formation is blocked would have a major climatic impact on the North Atlantic region. Quantitative knowledge of ocean circulation processes and understanding changes in the ocean fresh water budget will be needed to provide a reliable answer to this question.

- ***Are polar ice sheets losing mass as a result of climate change?***

Polar ice sheets, principally over Greenland and the Antarctic continent, constitute the largest reservoir of fresh water on the planet, corresponding to about 2% of the mass of the global oceans. Change in the mass balance of these ice sheets would result in major changes in the global volume of ocean waters and global sea-level. Airborne surveys of the Greenland ice sheet show little elevation change over most of the interior of the ice sheet above 2000 meters in height, but some areas of significant elevation change – predominantly thinning – around the coast. Assessing the rate of change of the much larger Antarctic ice sheet remains a major challenge, which can only be met through combined space-based topographic surveys and supporting *in situ* measurements or model estimates of variations in snow accumulation.

- ***Will changes in polar ice sheets cause a major change in global sea level?***

While an evaluation of the mass balance of the ice sheets is important for determining their current behavior and contribution to sea level change, any understanding of their likely future behavior requires an understanding of their dynamics and sensitivity to external forcing. The traditional concept of continental ice sheets as a sluggish component of the Earth system, changing literally with "glacial" slowness, is being superseded by the realization that parts of the ice mass are actually capable of changing substantially over periods of a few years or decades. The dramatic calving of vast tabular icebergs from relatively unstable ice shelves surrounding the Antarctic Peninsula is a portent of such changes. The first high-resolution radar survey of the Antarctic ice sheet discovered massive ice-streams, huge rivers of ice reaching far inland and leading to the ice sheet margin. Assessing the potential for relatively fast ice flows that could discharge vast volumes of ice in a matter of decades instead of centuries is a portentous problem, considering the global consequences of a possible acceleration of sea-level rise.

5.2 SCOPE AND NATURE OF THE PROBLEM

Climate research actually addresses two distinct scientific problems. The first problem is that of understanding and predicting climatic variations that form part of the natural variability of the Earth system, on time scales from a few months or years to decades and centuries. The second problem is determining the extent to which known or anticipated changes in climate forcing factors (e. g. the composition of the atmosphere) can influence global climate. There is no evidence that the intrinsic (unforced) variability of the atmospheric circulation can, by itself, induce persistent and predictable climate changes: statistically significant climate variations must therefore be governed by the slower components of the climate system, or driven by changes in external forcing such as transient increase in stratospheric aerosol loading caused by a volcanic eruptions. Understanding climatic variations requires knowledge of the dynamics of the slow components of climate, principally ocean and ice. The effects of anomalous hydrologic conditions over continents also can persist over periods of weeks or months, but barely qualify as "slow" in this context (see Chapter 4). The effects of changes in terrestrial ecosystems can last for longer time periods, but the nature and amplitude of resulting climate impacts are still unclear (see Chapter 2).

Any conceivable scientific strategy to explore the full range of climatic variability must rely, at some stage, on artificial records generated by numerical models of the interactive atmosphere, ocean, ice and land system; accumulating observational records over decades or centuries is not a realistic option for immediate results and paleoclimatic/historical information is generally insufficient to reach definitive conclusions regarding the operative mechanisms. While satellite observations afford us a global view, model simulations give us access to the time dimension. The problem is that of constructing, for instance, sufficiently realistic models of the global ocean circulation on the basis of a relatively brief observational record or "snapshot" of the evolution of the natural system. The development of fully coupled Earth system models that could be used with confidence to investigate the variability of the climate is considered in Chapter 7.

5.2.1 Global Ocean Circulation Variability

Sea surface temperature (SST) is a principal governing parameter of air-sea interaction and the first global indicator of change in ocean circulation and climate. SST variability is the result of radiative transfer (shortwave and longwave heat fluxes), air-sea interaction (sensible and latent heat heat fluxes), mixing of surface waters (entrainment), and horizontal movement of ocean waters (advection). SST is known to vary strongly on interannual time scales in the tropical Pacific Ocean (e.g. El Niño) and to vary coherently on decade-centennial time scales in Atlantic and Pacific Oceans. In the Atlantic cold and warm epochs coincide with variations of the North Atlantic Oscillation (NAO). In the Pacific a broad meridional SST variation has been identified with longer time scales than El Niño, referred to as the Pacific Decadal Oscillation (PDO).

The ***extent of sea-ice*** over the polar oceans is also a sensitive indicator of climate change, as the annual cycling of the ice cover is determined by a finely tuned balance between radiant heat loss, heat exchanges with the ocean and atmosphere, and the absorption of solar radiation during summer (the latter being strongly dependent upon the rapidly changing optical properties of dry or melting snow and ice). Recent observational evidence indicates not only a significant decreasing trend in the extent of sea ice over the Arctic ocean, but also a decrease in mean sea-ice thickness. The permanent disappearance of summer sea ice in the Arctic, a distinct possibility under plausible climate warming scenarios, would have a major amplifying effect on global warming at high northern latitudes. Both sea surface temperature and the extent of sea ice are routinely monitored by operational observing systems.

Knowledge acquired in the past about ***ocean currents and sea level*** was derived from *in situ* oceanographic and tide gauge observations available from a limited set of coastal stations or oceanographic cruises. Only space-based observation can provide the global coverage, spatial resolution, and sampling frequency necessary to capture the full range of variability in the surface circulation of the global ocean. Space-based measurements of the height of the ocean surface provide information on the combined effects of expansion or contraction of the water column due to changes in water properties and changes in mass above the reference surface (geoid) such as those associated with the wind driven circulation. Altimetry reveals changes in the sub-surface temperature structure and heat content of the ocean, as was observed in the tropical Pacific before the inception of the 1997-98 El Niño event, thus allowing reliable prediction of this climate event.

Accurate knowledge of the Earth's ***gravity field*** and ***the Earth's center of mass*** is also necessary to translate the raw satellite altimetry data into useful dynamic information (height above the reference surface for gravitational potential or "geoid"). Gravity field data expected from the forthcoming GRACE mission will raise our knowledge of the geoid to a new level of accuracy, comparable to the precision of altimetric measurements. In the future, it is anticipated that further technical advances will enable detecting transient changes in the Earth gravity field, effectively measuring the gravitational signature of changes in mass distribution at the surface of the planet. Such gravity measurements will enable mapping the time-dependent distribution of ocean mass (in effect ocean bottom pressure) and reveal more about ocean mass transport.

Pacific Ocean and the Southern Oscillation

The El Niño-Southern Oscillation (ENSO) phenomenon is governed by the basin-wide response of the tropical ocean circulation to anomalous surface winds, and the (local) response of the tropical atmosphere to circulation-induced changes in sea-surface temperature. While the active core of the phenomenon is localized in the tropical Pacific ocean, ENSO is a coherent global oscillation which is felt worldwide, and more strongly so in Australia, Southeast Asia, and the Americas. The basic ENSO mechanism is well enough known that predictions can be made several seasons in advance, using *in situ* observations and space-based measurements (especially ocean surface topography and winds). Past climatological record shows considerable decadal to centennial variations in the recurrence frequency and strength of ENSO phenomena. For instance, the two largest known El Niño events of the century have occurred during the last 15 years. It is not known whether this was a random occurrence within the normal range of natural variability, the result of a multi-decadal transient anomaly in the circulation of the Pacific ocean (an hypothetical "Pacific Decadal Oscillation"), or a consequence of global climate warming. Investigating the long-term variability of the ENSO phenomenon will require much deeper understanding of dynamics of basin-wide oceanic circulation and the physics of air-sea interaction. Both present major scientific challenges.

5.2.2 Change in the Deep Ocean Circulation

The oceans constitute by far the largest heat reservoir in the Earth's climate system. Any excess energy in the net planetary radiation budget is absorbed principally by the oceans, thus causing a progressive warming of ocean waters. Depending upon the depth reached by this ocean warming, the effective thermal inertia may be smaller or larger, determining the time delay before temperature rises at the surface. Furthermore, the thermal expansion coefficient of ocean water, which determines the change in the total ocean volume for a given heat intake, depends upon temperature and depth; detailed knowledge of the total water column ocean circulation is essential for a reliable assessment of future sea-level rise and its variation globally. Finally, ocean water subduction entrains carbon into the deep ocean, while oceanic upwelling brings nutrient-rich deep waters near the surface. The geographical location and temperature of upwelling waters are controlling factors in the planetary carbon cycle and atmospheric carbon dioxide, marine ecosystems and, eventually, fisheries.

Mechanical stress produced by wind is the principal driver of upper oceanic motion on all scales, from oceanic turbulence and upper ocean mixing to basin-scale currents. Because of the nonlinear interactions linking different scales, accurate simulation of the ocean circulation requires detailed knowledge of ocean surface wind at relatively fine space and time scales. The rotational component of the wind stress induces vertical upwelling motions that play a major role in thermal and chemical balance of the oceans. While wind stress is the principal driving force in the upper ocean, the deep ocean circulation is largely thermohaline (i.e. largely controlled by the temperature and salinity structure of the ocean). The formation of deep water from saline surface water exposed to cold air is the primary mechanism that drives the deep ocean circulation connecting all ocean basins. The circulation time scales of deep waters range from decades to millennia, thus making the deep ocean circulation the principal physical agent in long-term climatic variations and long-term trends.

Deep water formation is expected to be sensitive to freshening of surface waters, brought about either by the import and subsequent melting of sea or land ice, or by climate-induced changes in the fresh water balance of the ocean at tropical and mid-latitudes. Since atmospheric temperature at high latitude always falls below the freezing temperature of sea water, the fate of superficial waters and their ability to sink into the deep ocean depends upon their pre-existing salinity (salinity and temperature are the two parameters that determine water density). Thus, the principal observational requirements for investigating the potential for a transition in ocean circulation regime are (exploratory) measurements of ***sea surface salinity*** as well as observations of ***sea-ice*** formation, transport and melting processes**.**

Air-Sea Interactions

The physical characteristics of deep ocean waters are largely governed by air-sea interaction at high latitude, while many of their chemical characteristics are determined by the downward flux of biogenic material. Determining the heat, momentum, and fresh water fluxes at the ocean-atmosphere interface is a major challenge of climate research, basically because of the wide disparity in the masses and heat capacities of the two media. The atmosphere may respond to surface flux anomalies on the order of 10-100 Watt/m^2 over periods of days. The oceanic circulation responds, over periods of years, to time-averaged net energy fluxes on the order of a few Watt/m^2 or net water fluxes (precipitation minus evaporation) one or two orders of magnitude smaller than instantaneous rainfall or evaporation. Air-sea fluxes are traditionally computed by means of bulk aerodynamic formulas involving surface wind and near-surface vertical gradients of the relevant properties. Such simple aerodynamic formulas cannot be legitimately extrapolated to data-sparse areas, using global remote sensing data sets that do not resolve near-surface gradients, or information from models that do not reproduce relevant boundary layer processes. Much progress will be needed in both global observation of the marine atmosphere and model computations of surface fluxes to advance in this domain.

North Atlantic Climate Change

The analysis of atmospheric and oceanic records has revealed a coherent pattern of decadal variability in mid-latitude winds in the northern hemisphere, together with variations in sea-surface temperature (SST) and sea-level pressure over the North Atlantic, including occasional incursions of sea-ice and salinity anomalies from the Arctic. This "Arctic Oscillation" of the global atmosphere, also referred to as the "North Atlantic Oscillation" over the region where the most active air-sea interaction occurs, influences weather in North America and Europe and may be related to changes in precipitation over the African continent and Brazil through tropical SST variations. No definitive indication exists at present of the nature of underlying mechanism(s). On longer time-scales, coupled atmosphere-ocean model simulations suggest a significant weakening of the meridional overturning circulation and heat transport in the Atlantic ocean basin, that may change the current mild climatic conditions existing at high northern latitudes over the Atlantic seaboard and Europe. The immense economic disruptions that would result from such climate change make the long-term stability of the Atlantic ocean circulation a highly charged geophysical research issue.

Antarctic Circumpolar Wave

Sea-ice dynamics is usually perceived as a short-period response to wind, radiation or oceanic forcing fluctuations, but longer period variations do exist. The recently discovered Antarctic Circumpolar Wave is such an oscillation in sea ice-extent and local concentration, accompanied by related variations in surface wind and sea-surface temperature, that run a full circuit around the Antarctic continent in about 8 years. No atmosphere-ocean-sea ice coupling mechanism has yet been identified to conclusively explain this phenomenon. Similar propagation of disturbances in the edge of the ice pack has also been observed in various regions of the Arctic.

5.2.3 Mass Balance of Polar Ice Sheets

General sea-level rise results from the thermal expansion of ocean volume and/or addition of meltwater from mountain glaciers and polar ice sheets. Sea level change at a particular site may also reflect changes in ocean circulation (a 50cm rise in sea level at some Pacific island sites may result from ENSO events), as well as geological processes such as continental uplift or subsidence. Crust rebound rates from lifting the ice load accumulated during the glacial period are as large as 1m per century at some locations around the coast of Scandinavia. The scope for serious environmental impacts is obviously very large, since a large fraction of the world population resides in coastal areas. Even a 10cm rise, as anticipated in the next 30-50 years, will threaten coastal wetlands, increase the exposure to storm surges and wave damage, induce increased coastal erosion and allow substantial encroachment of salt water in near-shore aquifers. Numerous cities built near the sea-shore in region subject to geological subsidence are now very sensitive to further sea-level rise.

The well-documented retreat of alpine glaciers since the climax of the Little Ice Age is the most dramatic early indicator of a global climate warming trend. Total melting of remaining mountain glaciers would only raise the global mean sea-level by an additional 50cm. On the other hand, mountain glaciers are retreating fast and their contribution to sea-level rise could be larger than the contribution from polar ice sheets through the next century.

The melting of the ice stored in the Greenland and Antarctic ice sheets would be sufficient to raise the level of the world ocean by 75m. We know that ice sheets alternatively advanced and retreated during several million years, causing changes in global mean sea level in excess of 100m. We also know that any net change currently occurring in ice sheet mass balance must be quite small, consistent with a rate of sea-level rise on the order of a few cm per century. Yet, during the period of recovery from the last glacial maximum, sea level rose at a rate exceeding 1m per century. Very little is known, quantitatively, about the dynamics of the polar ice sheets, the input and output terms of their mass balance and the potential for rapid evolution, given the range of potential changes in polar climates.

The goal is to quantify (or confirm the absence of) relatively fast changes in the mass balance of polar ice sheets and this implies measuring the total volume of the ice sheets and their flux. NASA has made significant progress in developing instrumentation to support this objective and satellite observing techniques including precision lidar altimetry and radar imaging have recently become available. These techniques will be used to survey both major ice sheets and will acquire information comparable to that already derived by NASA from aircraft observations over the Greenland ice sheet.

5.2.4 Ice Sheet Dynamics and Sea-Level Rise

In the traditional view, the rate at which ice sheets could conceivably deliver water to the ocean is inversely related to their size. This reassuring view may turn out to be short-sighted, as it ignores the relatively fragile equilibrium of parts of the polar ice sheets, such the West Antarctic marine ice sheet, and the existence of 1000km long ice streams that reach far inland and could drain ice much faster than the traditional picture would imply. Currently, the combined uncertainty in the mass balances of the Greenland and Antarctic ice sheets is larger than the uncertainty about sea-level rise from all other causes. The recent break-up of large ice shelves fringing the Antarctic Peninsula have focused attention on the possibility of a collapse of additional ice reservoirs further south within a relatively short time period. Changes in floating ice shelves will not affect sea level directly, but their break-up would allow the ice sheet upstream to flow more freely toward the ocean. The observational requirement is mapping the ***velocity fields*** of the two great ice sheets of Greenland and Antarctica in order to identify their dynamic regions and estimate the mass fluxes of major ice streams. The relevant (synthetic-aperture radar) data might be obtained commercially, or from dedicated national or international scientific measurement missions. Regional airborne campaigns that are able to shed light on the internal and basal properties of major ice streams will complement such spaceborne campaigns and will support the development of models.

EXPECTED SCIENTIFIC ACHIEVEMENTS

Question 1: How is the global ocean circulation varying on climatic time scales?

Expected new knowledge in the next 5 years
- High-resolution structure of the global ocean surface wind field;
- Global upper-ocean circulation data assimilation and prediction, including ENSO forecasts with ocean-atmosphere coupled models;
- Improved coastal ocean predictions through assimilation of global and local data;
- Global diagnostics of transient sea-ice cover and flux anomalies.

Expected new knowledge in the next 10 years
- Estimation of the state of the world ocean circulation down to eddy-scale motions, based on model assimilation of global ocean data;
- Linkage between the global ocean circulation and the frequency and intensity of ENSO events;
- Linkages between sea ice anomalies and high latitude atmosphere and ocean anomalies.

Question 2: Will climate variations induce major changes in the deep ocean?

Expected new knowledge in the next 5 years
- Global diagnostics of transient sea-ice cover anomalies;
- Experimental global diagnostics of sea-ice thickness;

Expected new knowledge in the next 10 years
- Relationships between global sea-surface salinity, riverine inputs, sea ice anomalies and deep water formation rate;
- Linkage between the Atlantic Ocean circulation and global atmospheric climate.

Question 3: Are polar ice sheets losing mass as a result of climate change?

Expected new knowledge in the next 5 years
- Baseline high-precision data base of Greenland and Antarctica elevations;
- Estimation of the current mass balance of the Greenland ice sheet;
- Current trend in global mean sea-level based on a ten-year record of satellite altimetry data.

Expected new knowledge in the next 10 years
- Development of models relating high-latitude climate to mass loss/gain over both polar ice sheets;
- Baseline determination of the total mass of the Antarctic Ice Sheet;
- Estimation of the mass balance of key Antarctic catchments.

Question 4: Will changes in polar ice sheets cause a major change in global sea level?

Expected new knowledge in the next 5 years
- High resolution maps of Greenland and Antarctic ice streams and estimates of flux for major catchments;
- Initial development of models of ice stream dynamic behavior

Expected new knowledge in the next 10 years
- Description of ice stream dynamics and sensitivities to external forcing;
- Data analysis and models relating ice sheet accumulation and mass loss to climate

5.3 PROGRAM ELEMENTS

Common to the four scientific questions formulated above is the need for an effective inter-agency as well as international research strategy, such as laid out by the World Climate Research Program: no single nation, let alone science-funding agency, has the means to investigate climate problems of such global extent and multi-disciplinary scope. The NASA effort currently focuses on global measurements of the ocean circulation and the mass of polar ice sheets, and seeks fundamental understanding of the dynamics of these slow components of the climate system. Currently, a special effort is devoted to understanding and predicting ENSO phenomena (and other short-term climate variations). As global ocean modeling capabilities and computing resources develop, the research effort is expected to shift toward investigation of ocean and ice dynamics on longer time-scales.

Characterizing and understanding the current variations in global ocean circulation calls for new global space-based observations of oceanic variables, as well as development of modeling tools to assimilate such satellite data together a wide range of contemporaneous *in situ* oceanographic measurements. The principal thrust NASA research in this domain will be understanding the dynamics of the ocean circulation and developing the capability to predict the response of the ocean circulation and sea ice to changes in surface forcing, on the basis of relatively short global oceanic data sets spanning only 10-20 years. As global oceanography is still in a development stage, scientific progress is critically dependent upon new global observations of the ocean circulation, sea-ice, and surface fluxes of momentum, heat, and fresh water (see Section 5.3.1).

Understanding the response of the deep ocean circulation to climate change is an even more difficult problem, involving in a crucial way the coupling with the atmospheric circulation, energy transformations, and water budget, as well as internal ocean processes. The principal thrust of the NASA program will be acquiring global observations of ocean and sea-ice properties (sea surface temperature, salinity, and winds; sea-ice deformation and thickness) and enable inferring the heat and fresh water budgets of the ocean (see Section 5.3.1).

Assessing current changes in the mass balance of polar ice-sheets calls for advances in quantitative characterization of year-to-year changes in ice sheet topography and estimates of annual snow accumulation and mass losses, based on supporting snow and ice core data, ice velocity maps, iceberg discharge data, model assessments of precipitation, etc. It is particularly important to establish the inter-annual variability in snow accumulation and ice losses in order to understand the significance of mass balance estimates. In the course of the past ten years, NASA has participated with NSF and other science funding agencies abroad in the study of the Greenland ice sheet, and has spearheaded a systematic Greenland *in situ* and airborne survey program (NASA, 1999) to determine current trends in the Greenland ice-sheet mass balance. The focus of the NASA contribution will be the extension of these surveys to the Antarctic ice sheet, using satellite-based precision altimetry and gravity measurements (see Section 5.3.2).) and continued efforts to establish effective satellite-based methods for mapping snow accumulation and ice loss.

Understanding the dynamics of ice sheets is important in order to evaluate the susceptibility of the ice sheets to future changes in mass balance. In particular, it is important to understand the extent to which ice streams, which transport most of the ice mass into the oceans, are sensitive to external forcing. There is clear evidence for past changes in the dynamics of ice streams and for current changes in the positions of some grounding lines, where ice streams begin to float. It is likely that some of these changes may reflect internal dynamics, but it is not clear whether this behavior is sensitive to more extreme changes brought about by external forcing. In order to understand the likely level of stability of the ice sheets, it is necessary to support radar mapping of surface ice velocities to reveal the area extent of the ice streams (Section 3.3.4) and to understand the internal and basal dynamics of ice streams by radar sounding and modeling. In understanding the stability of the major ice sheets, it is also important to establish the extent to which snow accumulation and ice loss is sensitive to changes in climate. This will require continued efforts to model interactions between snow accumulation, ice melting and climate at high latitudes.

5.3.1 GLOBAL OCEAN CIRCULATION AND SEA-ICE

The first global survey of the world oceans, completed by the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean Global Atmosphere (TOGA) programs of the World Climate Research Program, provided a description of the state of the global ocean circulation in the 1990's. The scientific community is now poised to effectively begin experimental time-dependent predictions of the global ocean circulation and its interaction with the atmosphere and cryosphere, in order to:

- Understand and predict how the oceanic circulation may affect sea surface temperature on time scales from days to years.
- Understand and predict how variations in atmospheric and oceanic circulation determine interannual and decadal fluctuations in the extent of sea–ice, as observed in the historical record.
- Assess the impact of changes in oceanic circulation on marine living resources, and
- Estimate how the oceanic circulation may influence the global carbon cycle and sea level.

This program requires time-series of global ocean/sea-ice data covering periods comparable to the characteristic time-scales of oceanic gyres (several decades). Estimating the full-depth global circulation of the ocean requires the synergistic application of multiple techniques: global observation of ocean surface parameters from space; *in situ* observation of the ocean density structure and transport (current velocity field and tracers); assimilation of ocean data from a variety of sources using ocean circulation models; and long-term simulation runs with high-resolution ocean circulation models (computing technology is the limiting factor). NASA supports this global ocean circulation research strategy and aims to contribute, together with operational environmental agencies and other partner agencies, to the realization of an ocean observing system combining *in situ* measurements with space-based observation, data processing and analysis.

5.3.1.1 Systematic Global Ocean Measurements

Consistent with the research strategy outlined above, the highest scientific priority in the discipline is systematic global measurement of five critical ocean surface variables that can be used, in conjunction with *in situ* oceanographic observations, to reconstruct the global ocean circulation: sea surface topography or dynamic height, vector winds, sea surface temperature, and sea ice concentration and dynamics. Measurement of these variables from space has already been demonstrated with the required accuracy and coverage. Satellite remote sensing is the only means to acquire almost instantaneous worldwide observations and thereby provides the appropriate diagnostic tool for understanding the time-dependent circulation.

Ocean Surface Topography

Ocean surface altimetry data provided by the NASA/CNES TOPEX-Poseidon mission (1992-present), the European ERS satellite series (1991 to present), and US Navy GEOSAT-1 (1985-90) ushered a new era of global dynamic oceanography, based on successive synoptic mappings of ocean surface height and the geostrophic ocean circulation. NASA plans are based on the prospect that altimetric measurements of sea level topography will eventually evolve into a component of an operational ocean observing system. The implementation of this measurement from operational environmental satellites in sun-synchronous polar orbit faces two unresolved technical problems:

- Correcting the effect of solar tides (aliased in sun-synchronous measurements) to the required accuracy of a few centimeters by means of a suitably advanced global tidal model.

- Providing the required space-time sampling of the most active ocean circulation features, as provided by the optimal TOPEX orbit

Pending the resolution of these questions, NASA plans to expand its cooperation with France and US agencies to continue small satellite missions dedicated to ocean altimetry. The TOPEX-Poseidon altimetry satellite continues to provide precision sea level data of 3-5 cm (RMS) accuracy, that are incorporated in the NOAA and NASA ENSO prediction systems (NASA Seasonal-to-Interannual Prediction Project). The follow-on program, beginning with the Jason-1 mission (to be launched in May 2000), is aiming to improve upon this accuracy and reduce the uncertainty to a 2cm (RMS) level. A principal objective of this and follow-on missions is to foster operational uses for a variety of applications, from ocean circulation prediction (coastal current, ENSO forecasts, etc.) to geophysics.

It is presently envisioned that the successor Jason-2 mission could be a cooperative effort of the US and French space agencies, with the participation of operational agency partners. Jason-2 would prolong for a nominal five year period the time series of high-precision altimetry data initiated with TOPEX-Poseidon and Jason-1 (Box 7). Although significant further work will be needed to develop a real-time acquisition system for a high-quality ocean altimetry data, and assimilate effectively these data in ocean models, active steps are being taken, notably under the Global Ocean Data Assimilation Experiment (GODAE), to ensure that operational applications are practical and widely accepted. The real-time availability of precise sea-level measurements from space is the innovation that makes operational oceanography viable, and justifies a national initiative to create a global ocean observing program combining the resources of research and operational agencies (see Section 3.3.1.3).

Box 7
Ocean Surface Topography Mission

Based on the heritage of the very successful TOPEX/Poseidon radar altimetry mission, the Jason-1mission is a joint project of NASA and the French space agency CNES. Jason-1 will carry a two-frequency radar altimeter derived from the CNES-provided instrument on TOPEX/Poseidon, as well as a microwave radiometer for simultaneous measurement of total water vapor in the air column. The latter is necessary in order to correct significant spurious propagation delays introduced by natural variability in atmospheric water content.

Jason-1 and subsequent repeat missions will be placed on the TOPEX/Poseidon orbit (1336 km altitude, 66° inclination circular orbit) that provides optimal time and space sampling of the active dynamical components of the oceanic circulation and ocean tides. The objective is to enhance the altitude determination accuracy and reduce residual errors to 2cm RMS in calm to moderate sea state conditions.

Ocean Surface Wind

The wind vector field over the surface of the ocean constitutes an essential boundary condition to drive ocean circulation simulations and predictions. Both active (scatterometer) and passive (polarimeter) microwave measurement techniques can be applied to determine vector wind. The wind vector accuracy (of order 1 m/sec over the full range of wind speeds) required in principle for global ocean dynamics prediction remains to be demonstrated by either technique, however, although scatterometer wind data are close to this goal. Building on the heritage of the NASA Scatterometer (NSCAT) sensor flown on the Japanese ADEOS mission in 1996-1997, the agency has developed a successor instrument (Seawinds) which will fly on two overlapping missions: QuikScat (launched in June 1999) and Japan's ADEOS-2 to be launched in late 2000. At the same time, the Navy is preparing a experimental satellite mission (Coriolis) to test the passive microwave technique for vector wind finding applications (see Box 8). Further improvement of the NASA wind scatterometer is contemplated with a proposed AlphaScat sensor that could fly on Japan's follow-on Global Change Observation Mission (GCOM B-1) in 2005.

The Seawinds missions will be followed in 2003-2004 by the operational deployment of the ASCAT wind scatterometer sensor (developed by the European Space Agency) on the European METOP environmental satellite series. Further downstream, the NPOESS program is planning to deliver daily quasi-global vector wind data based on passive microwave polarimetry (Conical-scanning Microwave Imager/Sounder). NASA may continue its cooperation with Japan to maintain a capability for precision global wind observation based on active microwave measurements on Japan's GCOM environmental research satellite series.

Box 8
Ocean Surface Wind

NASA has launched the Seawinds wind-finding microwave scatterometer on its QuikScat mission (June 1999) and provided a model of the same instrument for flight on Japan's ADEOS-2 mission in late 2000. The second generation Seawinds instrument is expected to provide unequalled precision (on the order of 1-2 m/sec), horizontal resolution (25 km) and a broad swath width allowing daily coverage of the world oceans with minimal gaps.

Pending the results from the Seawinds (active) and Coriolis (passive microwave) wind remote sensing demonstration projects, NASA is studying the opportunity of deploying an advanced technology version (AlphaScat) of its current wind-finding scatterometer on Japan's Global Change Observation Mission (GCOM) satellite series and/or future NPOESS operational satellites.

For the future, an alternative method based on surface scattering of GPS signals shows promise as a means to estimate surface winds globally with unprecedented spatial and temporal resolution. Research on GPS reflection and scattering phenomenology is a priority research avenue for NASA's physical oceanography program.

Sea-Surface Temperature

Sea surface temperature (SST) is the only property of the open ocean that directly affects the general circulation of the atmosphere. SST is also very sensitive to changes in ocean circulation, as demonstrated time and again by wind-driven ENSO events. For these reasons, and also because sea surface temperature has been measured quite accurately by ocean-going vessels over a period of several centuries, long-term SST records are a most valuable source of information on climate variability and trends. Quasi-synoptic global SST fields are derived operationally, for a variety of applications, by merging global radiance measurements from operational satellites (NOAA/AVHRR) and *in situ* observations by ships of opportunity and a relatively thin network of moored and drifting buoys. The climate science community currently depends on these operational SST products for climate and physical oceanography research, even though the accuracy achieved in this operational context (0.5-0.7°C) is marginal for some scientific investigations (in the tropics, a 0.2-0.3°C temperature anomaly may be enough to change evaporation materially).

Improving the precision of SST remote sensing is essential to achieve adequate and essentially uniform accuracy worldwide, even in regions where *in situ* measurements are scarce. Significant progress is expected with the MODIS radiometer on EOS Terra and Aqua, on account of the sophisticated on-board calibration and accurate corrections for atmospheric water vapor and aerosol. Equally significant improvement in SST retrieval is also expected with the Atmospheric Infrared Sounder (AIRS) on EOS Aqua on account of superlative ability to correct for atmospheric absorption. Atmospheric corrections are considerably smaller for microwave radiometry: the significant advance demonstrated with TRMM Microwave Imager (TMI) measurements, and further technical refinements expected with the Advanced Microwave Scanning Radiometer (AMSR) on the EOS Aqua mission and the Advanced Technology Microwave Sounder (ATMS) on the NPP mission (see Box 3) will allow combined retrievals of ocean surface wind speed (sea state) and temperature that can match and possibly improve upon the accuracy of current global SST retrievals. NASA will continue to experiment with both infrared and microwave radiometry techniques for precision remote sensing of SST in the coming decade.

Sea-Ice Extent/Concentration

Sea ice modulates planetary heat transport by insulating the ocean from the cold polar atmosphere, and also by modulating the thermohaline circulation of the world ocean through the process of brine rejection. Moreover, the high albedo of snow-covered ice further insulates the polar oceans from solar radiation and introduces yet another positive feedback in the climate system. Systematic global observation of sea-ice extent and concentration, inferred from passive imaging microwave radiometry data, has produced an invaluable 20-year record of global sea-ice concentration. There is strong scientific justification for continuing this type of observation in the future, notably for early detection of impacts of the global greenhouse effect on the climate of the polar regions. Time series of sea-ice concentration data are also critical for identifying interannual and decadal fluctuations that could point to the existence of significant changes in oceanic and atmospheric circulations at high latitude.

NASA will rely primarily on the Advanced Microwave Scanning Radiometer (AMSR) provided by Japan on the EOS Aqua mission and operational satellite sensors (DMSP/SSM/I; NPOESS/CMIS) to ensure the continuity of the global sea-ice concentration record. The EOS/MODIS sensor also has the potential for advances in remote sensing of sea-ice conditions, by virtue of its high spectral resolution and provisions for deriving effective high-latitude cloud masks. Dual polarization synthetic aperture radar (SAR) observations provide the potential to make a significant improvement in our capability to map sea ice type and particularly to resolve areas of thin ice where most of the heat flux takes place. Active microwave scatterometer observations, provided by ADEOS, QuikScat, and the series of European METOP operational meteorological satellites, can also provide sea-ice concentration information, albeit at slightly reduced spatial resolution. The agency will continue to support global climatological studies based on a range of passive and active microwave measurements (imaging radiometer and scatterometer) and basin-wide studies using higher resolution sensors (including SAR).

Sea-Ice Dynamics

Sea-ice constitutes a mobile layer over the surface of the polar oceans, driven by atmospheric and ocean forcing. The motion of this layer forms a large-scale pattern of circulation that evolves over periods of years. Changes in the large-scale circulation of the ice pack may provide insight in the response of the high latitude environment to, and in turn influence on, ocean and atmosphere circulation at lower latitudes. Wide-swath active microwave instruments (Seawinds) and passive radiometers (AMSR) have a demonstrated a robust capability for mapping sea-ice drift in the polar regions: NASA will continue to encourage investigations based on the analysis of these data to link high-latitude ocean and atmospheric dynamics to global climate.

The motion of sea ice creates patterns of ice convergence and divergence that play a critical role in determining energy and momentum fluxes between the ocean and atmosphere at high latitudes. Furthermore, the production of new ice in areas of ice opening regulates the formation of deep water masses. High-resolution synthetic aperture radar (SAR) data constitute an ideal tool for basin-scale investigations of sea-ice motions, growth and deformation processes. The RADARSAT "Arctic Snapshot" program has provided SAR coverage of the majority of the Arctic every few days since 1996. These data are being ingested into the RADARSAT Geophysical Processor System and are generating large-scale sea-ice motion and deformation maps for the north polar region. Derived sea-ice products will be made available through the Alaska SAR facility and NASA will encourage the evaluation and broad application of these products by the polar community. SAR data will continue to assist in characterizing the detailed dynamics of Arctic sea ice and have the potential to reveal the dynamics of sea ice cover in the Southern Ocean.

5.3.1.2 Experimental Ocean Circulation Measurements

Precision Gravity Field or Geoid

Knowing the precise shape of the geopotential reference surface or geoid is essential in order to translate ocean surface altimetry data into absolute dynamic height information. The NASA Earth gravity mapping program (see section 5.3.2.1) will continue to use precision GPS receivers on geophysical research missions of opportunity led by international partner agencies to improve the determination of the earth gravity field at wavelengths of 1000 km or longer.

The experimental Gravity Recovery and Climate Experiment (GRACE) Earth System Science Pathfinder mission, currently being prepared in partnership with Germany, is expected to deliver more precise gravity field information (accuracy on the order of 1cm over scales of 300 km or longer). GRACE is also intended to measure, over a period of five years, minute variations in the Earth gravity field associated with transient changes in the distribution of fluid masses (see section 5.3.2.2). NASA is poised to exploit the extreme accuracy of present and future space-based gravity measurements to detect changes of the time-dependent distribution of ocean waters (equivalent to a global measurement of ocean bottom pressure).

Sea Surface Salinity

Ocean salinity, more than temperature, controls the dynamics of the deep ocean circulation and long-term climate. Sea surface salinity (SSS) determines the depth to which cold surface water may sink to form intermediate and deep ocean water masses. Despite the scientific significance of SSS, there is almost a total lack of systematic ocean salinity measurements worldwide, except for occasional oceanographic cruises and automated measurements on some merchant vessels. Thus, global remote sensing of SSS to a useful level of accuracy (better than 1 Practical Salinity Unit) would be a very significant achievement for global oceanography and global water cycle studies. Developing low-frequency microwave radiometry techniques for remote sensing of sea-surface salinity is a priority of the NASA physical oceanography program; aircraft test are being conducted to assess the feasibility of such measurement from space. The European Space Agency is currently studying a Soil Moisture and Ocean Salinity measurement mission (SMOS) that will test this measurement concept.

Alternative Approaches to Altimetry and Wind Measurement

The precision encoded transmission of the Global Positioning System has found many applications. Reflections of these signals off the sea surface are being examined for possible use as a source of wind speed and ocean surface topography information. The forward scattered GPS waveform depends on the roughness of the sea surface. The characteristics of the surface can be determined from the distribution of the reflected signal as a function of delay and Doppler. Wind speed is estimated using surface roughness models. Altimetric information can also be obtained although with significantly less accuracy than current radar altimeters. However, this measurement is still promising because of the significant increase in temporal/spatial coverage that might be obtained to complement precision altimetry missions. Scattering by the rough sea surface strongly attenuates the ocean-reflected GPS signal compared to that over a perfectly smooth ocean. For satellite reception, the large distance from the scattering surface accentuates this attenuation problem and significant increase in receiver antenna gain will be required and remains a technological challenge.

Sea Ice Thickness and Snow Cover

Sea-ice thickness and concentration are the primary variables for estimating sea-ice growth, melting, and mass transport by ocean currents (or equivalent fresh water transport), and for inferring energy and momentum fluxes across the ice-covered ocean surface. No current technique exists for the direct determination of sea-ice thickness from space. A new approach, using the RADARSAT Geophysical Processor System, is intended to estimate sea-ice thickness by monitoring ice divergence and convergence in Lagrangian cells moving across the Arctic and thence using an ice growth model to estimate ice thickness from ice age. The accuracy of such thickness estimates will depend critically on the reliability of the ice thickness growth model used in their derivation, as well as the accuracy of supporting meteorological information. The capability to acquire extensive measurements of sea-ice thickness represents the ultimate challenge of sea-ice remote sensing, as this quantity is so critical to the estimation of energy and momentum fluxes between the ocean and atmosphere.

Snow cover also plays an important role in determining the energy balance of sea-ice, as it adds substantial insulation from the atmosphere and modulates albedo. Yet, even the climatology of snow thickness distribution over sea ice is known only in the crudest terms. NASA will be interested in the development of experimental methods for estimating this parameter using space-borne sensors such AMSR. Ice surface temperature and albedo have also eluded routine observation to date, largely because of difficulties in separating cloud cover from snow and ice cover in visible and infra-red image data. New sensors such as MODIS may assist in addressing this problem.

Global Ocean Data Assimilation Experiment

The Global Ocean Data Assimilation Experiment (GODAE), currently in the planning stage, aims to provide a three-year demonstration of the usefulness of global ocean data assimilation products in the time-frame 2003-2007, utilizing real-time remote sensing and *in situ* data. If successful, GODAE will provide the proof of concept for operational ocean diagnostics and prediction on a global scale. This demonstration may include participation with other interested agencies, in the US and abroad, in the deployment of a basin-wide or global system of profiling floats, as part of the Array for Real-time Geostrophic Oceanography (ARGO) project. ARGO is an internationally sponsored project to deploy a global array of some 3000 ARGO profiling floats, that would complement global satellite observations and automatically acquire ocean temperature and salinity profile data. NASA will play a key role in developing the data assimilation component of GODAE, as needed to produce consistent analyses of the state of the oceanic circulation (see below).

5.3.1.3 Ocean and Polar Research Field Campaigns

Since ocean remote sensing is currently confined to its upper surface, *in situ* measurements are indispensable to characterize the vertical structure of the ocean and interpret the meaning of satellite data. This constraint will remain a reality over the coming decades and is the basis for strong interagency cooperation in the ocean research program. Over the last decade, NASA oceanographic process studies have been planned jointly with other federal agencies and embedded within the international World Climate Research Programme (WOCE and TOGA programs). Similarly, sea ice processes have been studied in partnership with other agencies, e. g. the NSF-led SHEBA ice camp project.

Future plans for ocean instrument deployments are being driven by the opportunity of GODAE. NASA is assisting in the design of the ARGO profiling float array and expects to be a primary scientific user of the data provided by that system. As a general rule, NASA will concentrate its resources on special-purpose ship- or aircraft-based field measurement campaigns focused on validation and testing of new remote sensing systems (e.g. remote sensing of surface salinity and sea ice properties). NASA is interested in the development of integrated in situ and space-based measurement systems and will support, to the extent possible, the development of the required technological capabilities.

NASA participated with NSF and other US agencies in a major, year-long field study of sea-ice and related processes (SHEBA ice camp project). This campaign provided a wealth of information on sea-ice growth, deformation and melting, sea-ice energy budget, and polar atmosphere and cloud properties. This information is currently being analyzed to determine the nature and importance of interactions between the ocean, ice and atmosphere and to establish and test methods for monitoring the polar oceans from space-borne sensors. The challenge will be to translate the results of these process studies to the scales of global circulation models. Future field campaigns are being envisaged by NASA, in collaboration with other agencies, to support *in situ* validation of satellite polar remote sensing products.

5.3.1.4 Global Ocean Circulation Modeling and Data Assimilation

Ocean model development in this program is closely linked to the analysis of global ocean data obtained from satellite and other observations. Synergistic use of models and data analysis is the principal approach for diagnosing the causes of ocean behavior or elucidating the physics of processes. NASA will maintain an active involvement in ocean model development and ocean data assimilation with the objective of providing a capability for estimating and predicting the state of the ocean circulation. This will be accomplished, in cooperation with NSF, by supporting the World Ocean Circulation Experiment (WOCE) analysis, interpretation and modeling activities. For the future, the principal focus for research and application will be the Global Ocean Data Assimilation Experiment (GODAE), currently in the planning stage. If successful, GODAE will provide the proof of concept for operational ocean diagnostics and prediction on a global scale. This work relies on a heritage of well-used community models and extensive engineering of the model efficiency. More general scientific and theoretical development of the model ocean circulation is supported as significant model deficiencies are occasionally demonstrated through data analysis. Treatment in global models of such subjects as the

Pacific-to-Indian Ocean flow through the Indonesian Archipelago, fluxes due to mesoscale eddies, and appropriate treatment of the weak deep circulation have motivated past NASA support. The potential of data assimilation will also be explored within the context of sea ice monitoring. NASA will continue scientific model development in the context of improving community models (see also Chapter 7: Earth System Observations and Modeling).

5.3.2 Ice Sheets and Glaciers

It is not known definitely whether the Antarctic and Greenland ice sheets are currently decreasing or increasing in mass. A high priority of the NASA research program on climate variability is to reduce the uncertainty in these measurements, and improve our ability to predict future ice-sheet behavior. The primary purpose of the ICEsat (Ice, Cloud and Land Elevation Satellite) mission, to be launched in July 2001, is to provide a baseline for estimating trends in the ice sheet mass balance by comparison with repeat measurements by later precision altimetry missions.

Many satellite data show promise for obtaining quantitative estimates of key ice-sheet parameters. Passive microwave sensors and scatterometers have offered insight into patterns of accumulation and ablation on the ice sheets while Landsat-7 and ASTER data will contribute to mapping of glaciers and their zones of melt and accumulation where higher spatial resolution is required. In recent years, SAR data has proved itself invaluable as a tool for exploring conditions across the great ice sheets. The twin European ERS missions and the Canadian RADARSAT Antarctic Mapping Project, in particular, have produced a wealth of synthetic-aperture radar (SAR) images of the Antarctic ice sheet.

The RADARSAT mission provided the first high-resolution radar map of the entire Antarctic continent, revealing information that promises to change the paradigm of Antarctic research. It is expected that a second Antarctic Mapping Mission, with an interferometric design, will allow the detection of significant changes in Antarctic topography and ice-stream velocity, thus providing further insight in the dynamics of the ice sheet (see Box 10 in chapter 6). Existing SAR systems have demonstrated a capability to derive velocity measurements of the surface even though they were not designed specifically for this purpose, and so while there are currently constraints on what can be achieved in terms of coverage and accuracy, the future utilization of SAR techniques is promising.

5.3.2.1 Systematic Ice Sheet Measurements

A key element of the NASA polar science strategy is the implementation of the ICEsat mission to measure changes in the elevation of the Greenland and Antarctic ice sheets. Observations from this mission will be used to evaluate changes in the surface mass budget and total ice volume, and to infer the contributions to sea level change (Box 9).

While the surface mass budget of ice sheets (snow accumulation, sublimation and/or melting) may vary with seasonal or interannual changes in polar climate, the ice dynamics varies over much longer time scales. ICEsat measurements of surface elevation are intended to provide the basis for an order of magnitude improvement in the accuracy of estimates of ice sheet mass balance and changes. The agency plans to repeat precision altimetric measurements at intervals of about 10 years, taking advantage of the increased accuracy that may accrue from on-going technical advances.

The agency has also, in collaboration with the Canadian Space Agency, demonstrated how powerful SAR data are in mapping the boundaries of the ice sheets and their surface dynamics, as well as in revealing surface features that were hitherto unknown (for example, giant snow “dune” fields). Repeated observations of the ice sheets by SAR, involving interferometric modes of observation that can be used for mapping surface ice dynamics, is a priority for NASA and will complement the altimeter missions.

5.3.2.2 Experimental Ice Sheet Measurements

Measurement of the ice sheet fluxes and mass balance depend on reliable estimates of ice sheet accumulation, ablation and dynamics. While there has been success in measuring surface dynamics and mapping areas of melt, snow accumulation rates over the ice sheets remain very uncertain. Effort will continue to develop methods for estimating surface accumulation rates from space.

Box 9
Precision Polar Altimetry Mission

The first precision altimetry mission, the Ice, Cloud and Land Elevation Satellite (ICESat) will be launched in July 2001 as part of the EOS program. ICESat will carry the Geoscience Laser Altimeter System (GLAS) and a GPS orbit determination system, to measure along-track ice sheet and land topography to an absolute accuracy of 10 cm or better, within a footprint of 70 m or less. The mission will also provide cloud profile information with 150m vertical resolution.

A repeat mission, focused on the primary science objective of measuring changes in the topography and mass balance of polar ice sheets, is planned in the 2010 time frame. The repeat mission may use a lidar altimeter similar to GLAS, or some other system that would enable precision altimetry measurements within a significant swath along the satellite track.

5.3.2.3 Field Measurement Campaigns and Ice-Sheet Process Models

NASA has played a leading role in supporting the application of airborne and field-based technology to studies of the Greenland Ice sheet, through the Program for Arctic Regional Climate Assessment (PARCA). Currently, surface-based and airborne measurements provide the only means to acquire certain critical ice sheet measurements, such as the depth and topography of the underlying terrain. Repeat airborne laser-altimeter surveys of the Greenland ice sheet have been conducted in 1998 and 1999 over the flight lines originally surveyed in 1993 and 1994. The laser altimeter technology allows areas of high relief to be surveyed, where highly dynamic outlet glaciers are often located. The repeat surveys provided the first clear indication of regional differences in ice sheet changes: conditions close to balance across the interior with some significant changes, predominantly thinning, around the margins.

Furthermore, NASA has supported the development of radar sounding techniques that are novel in being able to penetrate areas of “warm” ice that are close to pressure melting point, and hence has extended our knowledge of ice thickness to new regions of the ice sheet. NASA has also installed automatic weather stations on the Greenland ice sheet, to help interpret both aircraft and satellite data. It is foreseen that the acquisition of unprecedented high-precision ice topography, surface velocity and mass balance data will create a major body of information to support the modeling the ice sheets and glaciers. Prediction of future ice sheet changes requires that initial boundary conditions be known. Surface velocity as well as surface and basal topography are essential parameters that are needed for model initialization. NASA will provide these measurements through continued airborne (e.g. radar sounding) and spaceborne measurements. The NASA polar research program eventually aims to apply these techniques in conjunction with complementary NSF field measurements to key regions of the Antarctic ice sheet, as well as to other significant bodies of ice in the Arctic and sub-Arctic.

Field measurement campaigns are complemented by model studies of ice sheet processes and large-scale dynamics. The current focus of ice-sheet process modeling lies in understanding ice stream onsets and the sensitivity of the Antarctic ice sheet to ice shelf retreat. Full ice sheet models often do not adequately represent the dynamics of outlet glaciers and ice streams, which are the major source of ice discharge to the oceans. This can be partly attributed to the sparse measurements of key parameters (e.g. velocity and topography) with which to explore the physical processes that control ice flow. The stability of ice streams and the processes leading to their formation and maintenance, are critical in assessing the stability of the Greenland and Antarctic ice sheets as a whole. Ice streams are known to change significantly over periods of the order of a century; recent surveys carried out by NASA suggest that these features extend much further into the interior of the ice sheets than had previously been assumed. Ice shelves exert back-pressure on ice streams and have long been thought important to the overall stability of ice sheets, particularly the West Antarctic ice sheet. Both ice stream onsets and ice shelves remain priorities for modeling studies in tandem with observational campaigns.

5.4 LINKAGES

Linkages with other NASA Programs

The principal scientific linkage of Ocean and Ice research is with Global Water and Energy Cycle (GWEC) research activities outlined in Chapter 4. Altogether, the Ocean and Ice, GWEC, and the Earth System Observation and Modeling research themes (Chapters 4, 5, and 7) embrace the physics of the climate system. It is important to recognize that relatively small changes in mean climatological properties can induce marked changes in the frequency and/or strength of weather disturbances or sea level inundation: an essential requirement for practical application of climate prediction is the ability to link observed or predicted climate phenomena to significant regional weather and hydrologic events (Chapter 4). In addition, water mass formation links the global water cycle and climate to the slower oceanographic processes and freshwater transport in the ocean realizes the closure of the global water cycle on longer time scales.

The solid Earth and physical oceanography programs have a common interest in the measurement of the static and time-dependent components of the Earth's gravity field and contribute to understanding sea-level change (Chapter 6). A precise description of the geoid is required to infer relevant "dynamic height" gradients from relative topographic measurements obtained from altimetry satellites. In addition, measuring the variable component of the gravity field has the potential to provide global information about the ocean mass distribution (bottom pressure), water storage over continents or in aquifers, and the continental ice sheet mass balance. The precise measurement of the Earth's gravity field is the only remote sensing technique that does not rely on electromagnetic signals, and offers prospects for investigating the denser components of the Earth system.

The principal anthropogenic influence on climate is through changes in the cycling of carbon. The ocean is a vast buffer for atmospheric carbon dioxide and a sink for a significant fraction of the excess carbon dioxide flux generated by man's activities. The biogeochemical aspects of the oceanography program are addressed in Chapter 2, as well as the essential scientific linkage between ocean circulation dynamics and biogeochemistry. Important contributions to radiative forcing of the Earth climate also result from changes in the concentration and distribution of a wide range of chemically active trace gases (especially, ozone) and aerosols. Conversely, atmospheric transport and the chemical reactions that govern the distribution of trace gases are sensitive to the state of the atmospheric circulation and climate. The two-way interactions between atmospheric composition and climate are considered in Chapter 3.

Linkages with other US agencies

NASA's Ocean and Ice research is conducted in close coordination with other federal agencies participating in the US Global Change Research Program. This cooperation is particularly active in organizing the U.S. contribution to the study of Climate Variability and Predictability (international CLIVAR program). The Ocean and Ice research theme directly supports this major scientific initiative, also sponsored by NSF, NOAA, and the Department of Energy. Furthermore, NASA and NSF share a special interest in the analysis and synthesis of observations obtained by two major global oceanic research programs that are reaching completion, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS).

Another strong link is developing between NASA, NOAA, Navy, and NSF to support and organize a Global Ocean Data Assimilation Experiment (GODAE) aiming to demonstrate the feasibility and operational value of global oceanography in the period 2003-2007. It is likely that this joint effort will develop as part of the National Oceanographic Partnership Program, and may extend to include new domains such as the polar oceans (where these agencies are already cooperating in support of the International Arctic Buoy Program). Cooperation is also developing with the Navy and the DOD/NOAA National Polar-orbiting Operational Environmental Satellite System (NPOESS) for the measurement of ocean surface wind. It is expected that joint wind measurement research will emerge from the Navy/NPOESS Coriolis (passive radiometry) and the NASA Seawinds (scatterometer) experimental programs. In addition, NSF will continue to be a key partner for ice sheet research, following successful partnership in Greenland with the PARCA experiment. It is anticipated that this collaboration will extend to Antarctic field campaigns.

International Linkages

The Ocean and Ice research theme is closely aligned with the scientific goals and scientific strategy of the Climate Variability and Predictability (CLIVAR) and Arctic Climate System Study (ACSYS) components of the international World Climate Research Program. It is directly relevant to international assessments of climate change and the formulation of climate change scenarios conducted for the Intergovernmental Panel on Global Change (IPCC). By tradition, oceanography and polar research have always been truly international in scope and strongly reliant on cooperation between research institutions in sea-going nations and partners in the exploration of the Antarctic continent. The NASA research on climate variability and prediction builds on this tradition, again demonstrated by WOCE achievements in the recent past. In addition, several major bilateral cooperative programs or projects are being pursued with foreign agency partners, notably France (with the joint realization of the TOPEX/Poseidon ocean topography mission launched in 1992, and follow-on Jason missions), Japan for ocean wind vector measurements (NSCAT on Japan's ADEOS mission in 1996-97 and Seawinds on ADEOS-2), and Canada for radar mapping of the Antarctic ice sheet and the Arctic ocean (RADARSAT).

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CHAPTER 6

SOLID EARTH SCIENCE

6.0 INTRODUCTION

From a geophysical perspective, Earth is unique among terrestrial planets in that it is a dynamic system that contains abundant water and also supports life. Earth has profoundly evolved over the 4.5 billion years of its existence, constantly reforming its surface and overturning its interior with a vigor that is often disruptive to the life it supports. The basic structure of the Earth's interior was understood in some detail by the end of the 1930's; it was known that the planet has a metallic core, surrounded by a mantle of dense minerals, then by a less dense crust, and finally by thin oceanic and atmospheric layers. Yet the fact that every one of these components is in motion, manifesting a vast range of velocities over a diversity of scales, has only been known since the 1960s. A fundamental question is whether the distinctive dynamism of the Earth's interior has been a key influence in the continued presence of water and the development of life or, conversely, the presence of water had a controlling effect on the mechanical properties of rocks and the Earth's dynamics. To address this fundamental question, we must understand the mechanics of the Earth's interior and surface, and governing mechanical, physical and chemical processes.

Observations made solely from the Earth's surface had long hobbled scientific imagination. Gazing on quiet landscapes, the human perception of the Earth's dynamism was restricted to infrequent catastrophes - violent earthquakes, volcanic eruptions - or low key but persistent erosion processes. Today, the global perspective from space offers a new outlook, a planetary reference frame from which to precisely determine the slow overturning motion of the mantle; to observe the planet's magnetic field fluctuating with the turbulence of its liquid metal core; to measure changes in the length of day forced by ocean currents and global winds; to watch how continents strain in anticipation of an earthquake or volcanic eruption.

NASA's Solid Earth research program (NASA, 1991) examines the dynamics of the solid Earth at virtually all spatial and temporal scales, and aims to establish the scientific basis for reconstructing Earth's past history and predicting its future evolution. The overarching goal is to observe and understand the fundamental properties and processes of Earth's interior and crust which make it dynamic. The same effort also provides essential information to guide decision-making on issues of great human import by illuminating society's vulnerability to natural hazards.

NASA's objective in this domain is to contribute to scientific understanding and to provide technical leadership through pioneering space geodesy and remote sensing programs. The program requires highly accurate geodetic measurements to monitor the terrestrial reference frame, precise measurements of the static and time-dependent components of the Earth's gravity and magnetic fields, and observations of the Earth's surface geology, topography, and deformation with time. The program will improve the understanding of dynamical processes in the solid Earth and their interactions with other elements of the environment, including impacts on human societies and the assessment of vulnerability to natural hazards. In fact, the solid Earth science element is fully integrated with NASA's Natural Hazards program, as part of the overall "Solid Earth and Natural Hazard Program" of the Earth Science Enterprise. The scientific research effort is comprised of two major components:

- Understanding the fundamental geophysics and geodynamics of the Earth's interior and,

- Understanding global geological processes that shape the topographic surface of the Earth.

6.1 MAIN SCIENCE QUESTIONS

While geological and geophysical observations during the 20th Century have provided the general framework for understanding the nature of the Earth's interior and crust, they have left many fundamental questions unanswered about the physical properties of the inner components, that can be approached from a diversity of disciplines, including seismology, geodesy, geophysics and geochemistry, geologic mapping, sedimentary analysis, and laboratory studies. Within this multi-faceted research effort, NASA scientific activities focus on two main scientific questions:

- ***What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?***

The basic structural model of the Earth's interior, featuring a crust, mantle and solid/liquid core, largely evolved from the study of seismic waves. Owing in part to space-based measurements of contemporary crust motion and deformation, the plate tectonics model has become widely accepted, introducing the concept of rigid lithospheric plates that override the deformable interior (asthenosphere). Convection, governed by gravitational forces, is the accepted mechanism by which the mantle transports heat from the interior and drives plate motion. Despite this qualitative understanding, quantitative knowledge remains limited because the model is based largely on data describing millions of years of geologic evolution with relatively poor temporal resolution.

To gain a quantitative and predictive understanding of the mechanics of the Earth's interior, it is necessary first to infer internal heat sources and properties: temperature, viscosity, density, chemical and mineral composition. Fundamental knowledge is also needed of electromagnetic forces governing magnetic field generation, the coupling between mantle and crust, the physics of crustal deformation, the horizontal and vertical scales of convection, the time scales of change in convective motion, the role of chemical reactions and mineralogical transformations. Addressing these scientific issues requires studies combining laboratory investigations, numerical modeling, and a wide variety of observations taken on the ground, on ships and aircraft, and in space. NASA geodetic and geophysical measurement programs are part of a broad interdisciplinary effort to understand Earth's interior dynamics.

- ***How is the Earth's surface being transformed and how can such information be used to predict future changes?***

A conceptual understanding of the processes that have shaped the Earth's crust and topography has evolved from the recognition of influences from the Earth's interior, atmosphere, and hydrosphere. The present-day topographic surface of the Earth records the history of competition among sedimentation, erosion, land sliding, subsidence, sea level change, rock weathering, tectonics, earthquakes and volcanic eruptions. Surface topography also defines the boundary where the solid Earth interacts with the atmosphere, hydrosphere, and biosphere. The relative importance of the various landscape-forming processes, their interactions, and their time- or space-variability remain subjects of debate. Furthermore, their place in the evolution of the whole Earth, their effect on crustal deformation and mantle convection, and their role in the chemical differentiation of the planet remain uncertain. In addition to these fundamental geological questions, precise knowledge of surface topography and estimation of future changes are very important pieces of information for the pursuit of other environmental sciences such as hydrology, oceanography, and glaciology.

NASA's special contribution to this field of science is an integrated scientific approach, combining the application of global imaging and space-based geodesy with Earth system modeling. NASA's unique observing tools permit large-scale measurements, support quantitative analysis, and provide a global perspective that allows comparison among different regions of the planet. In addition, NASA is the source of fundamental geodetic reference data for a number of global programs in the US and internationally.

6.2 SCOPE AND NATURE OF THE PROBLEM

For convenience, the subject matter has been organized in the following two sections, recognizing that scientific problems may not necessarily fit exactly these categories. For example, topography expresses the integrated result of mantle convection and large-scale plate tectonics (solid earth dynamics), in addition to surface geological processes (weathering, erosion and sedimentation).

6.2.1 Solid Earth Dynamics

New and emerging insights into the internal workings of our planet result, in large part, from the analysis of simultaneous Earth gravity data, magnetic field measurements, and dynamic properties inferred from satellite observation. Although we now appreciate the intensity and ubiquity of circulation within the solid Earth, important features are yet to be fully understood. We do not yet understand whether mantle convection is layered or spans the whole depth of the mantle. We also aim to understand how mantle convection is coupled with the crust, and how gravitational (buoyancy) forces govern mantle convection that drives plate motions. The solid Earth holds many mysteries. Why are the inner and outer core rotating at different rates? What mechanism generates the magnetic field and why does the magnetic field, which remains relatively constant for hundreds of thousands of years, suddenly change and reverse its polarity? No single technique could provide enough information to solve these complex issues. A comprehensive approach, combining gravity and geomagnetic field measurements from a number of different sources with integrated global analysis and modeling, appears the most promising scientific strategy at this stage.

Changes in Earth's Rotation as a Measure of Fluid Motion in the Earth Interior

Until recently, interactions between the solid earth and the fluid core were a topic of speculations unconstrained by observation. That situation has changed, in part, because space geodetic measurements are now capable of detecting the signature of these interactions as changes in the rotational rate of the Earth as well as the position of the rotation axis within the Earth and with respect to inertial space. These observations also record momentum exchanges among the solid Earth, oceans and atmosphere, and the Moon, thereby contributing to understanding the structure of the core-mantle boundary, angular momentum changes due to core fluid motion, the nature of solid inner-core rotation, ocean and solid body tides, and liquid core oscillations.

Gravity Driven Mantle Convection

Departures of the Earth's gravity from the simple field of a homogeneous fluid rotating body are dominated by density variations related to convection. Thus, in addition to the basic configuration of crustal plates, oceanic ridges and trenches, the gravity field carries key information about the mechanics of mantle convection. At the moment, there is poor understanding of the relative roles of deeply penetrating "whole mantle" convection versus relatively shallow layered convection, and the horizontal scales of mantle convection cells. It is possible to estimate crustal thickness and infer physical properties such as lateral and vertical variations in viscosity and shear strength, by combining gravity data with information on deformation rates derived from space geodesy and topography data.

Magnetic Signature of Core and Lithosphere Properties

The existence of a magnetic field and its occasional polarity reversals have considerable theoretical interest in their own right (NRC, 1993). In addition, the magnetic signal provides insight into the internal structure, composition, and dynamic properties of the Earth's interior and the planet's ionized environment. The field near the Earth's surface is the sum of a main field generated by a fluid dynamo mechanism in the liquid core, remnant fields frozen in the crust, induced fields in the lithosphere, and field caused by time-varying external electric currents. It follows that, in order to interpret magnetic field observations, one must understand the main, remnant, and induced field components separately, and learn about the Earth's dynamics from each. The main field is virtually our only window on the workings of the liquid metal outer core, and its interactions with the solid inner core and the surrounding mantle. Changes over time measure core flow and are reflected, via core-mantle coupling forces, in Earth rotation changes. Numerical modeling of the complicated physics governing the core dynamo mechanism now provides a means to investigate the relationships between magnetic field, core flow, and earth rotation changes. The crust's remnant field records past magnetic field polarity reversals, the effects of plate tectonic motion, and the thermal history of the crust, but the physics governing these phenomena remain unknown. Induced fields provide information to improve the understanding of electrical conductivity, temperature and mineral composition of the mantle.

Large-Scale Deformation as a Measure of Mantle Convection

The plate tectonics model successfully explains many large-scale features of the crust, like mid-ocean ridges and ocean trenches, but fails to account for the distributed deformation field at plate boundaries, explain major earthquakes in plate interiors, and provide a complete description of vertical motions of the crust. This is largely because plate tectonics relies on evidence that is millions of years old and has poor temporal resolution. Further progress is expected from improved understanding of the Earth's contemporary dynamism and observations of crustal deformation at millimeter precision. The development of space geodesy, pioneered by NASA over the past two decades, provides this capability. NASA's space geodesy program has become the foundation of an international effort to measure the motions of the lithosphere and map the deformation of Earth's crust in three dimensions over time scales ranging from hours to years. The goal of these programs is to develop new comprehensive models of crustal motions that incorporate distributed plate deformation and take into account coupling to the underlying mantle flow. These models are expected to predict both horizontal and vertical motions and provide the mathematical framework for understanding earthquakes, volcanism, and landscape evolution.

6.2.2 Topography and Surface Change Processes

The processes at work within the Earth are manifested at the surface by changes in topography. Constructive processes, such as mountain building, earthquakes and volcanism, are balanced by erosion processes, giving rise to the landforms which provide the context for our daily lives. Understanding how these landforms originate and change provides insight in the ways human societies could accommodate to the changing landscapes.

The balance between accretion and erosion processes is, in itself, an important issue which warrants further investigation. How is this balance achieved and how does it evolve under varying climate conditions? What are the feedback mechanisms: how does climate affect erosion; how does erosion affect topography; how does topography affect climate? How do tectonics, erosion, and climate affect the course of rivers, their sediment load, and the evolution of beaches? How will sea-level rise or land subsidence affect this process? How can the geologic record of landforms be used, in combination with geodetic measurements, to quantify the frequency of seismic or volcanic events, assess their hazard potential, and consider human vulnerability to such geologic phenomena? While scientific insight can be derived from studying each of these events singularly, a globally integrated approach will provide understanding of their interactions and combined effects on the formation of the Earth's surface, as well as clues about the interior dynamics of the Earth.

Local Deformation and Earthquakes

Plate tectonics models can explain many large-scale features of the crust, as well as the observed large-scale motions of the Earth's surface. Detailed spatial and temporal distribution of strain within deformation zones and plate interiors can now be measured, but understanding the evolution of strain throughout the entire earthquake cycle remains a scientific challenge. Knowledge of the detailed development of topographic features, and their relationship to erosion, sedimentation, earthquakes, landslides, and surface geology, is necessary to understand the evolution of small- to intermediate-scale crustal features. Using space-based measuring techniques, it is now possible to monitor crustal deformation with millimeter accuracy, on spatial scales of meters to kilometers and time scales from minutes to years. This new observing capability fills the scale gap between traditional geologic mapping (motions on scales of hundreds of kilometers and millions of years) and the observation of catastrophic processes such as earthquakes (scales of meters and seconds). Natural laboratories, e. g. the distributed shear zone across Southern California, can serve as testing grounds for quantitative modeling of topography evolution, in addition to providing essential scientific data bases for earthquake vulnerability assessments.

Landscape Evolution

The forces that reshape the Earth's surface include sediment transport by wind and water, landslides, glacier erosion and transport of debris, volcanic eruptions, earthquakes and other tectonic motions. In addition, variations in the fluid content of sediments, due either to changes in ground water storage or to human activities (e. g. oil pumping), are often responsible for the measured vertical motions. Understanding the rates and magnitudes of these changes is challenging, but necessary if scientists are to predict the effects of natural or human-induced processes. Scientific understanding of sediment budgets, the impacts of severe storms, floods or human activities, and other processes related to landscape evolution, requires both a detailed view, obtained from field studies, and a macroscopic view provided by space observation. In addition, the perspective of space allows analysis and intercomparison of geologic features on a global scale, and often reveals spatial patterns that are not evident from the ground.

Global Sea Level Variations and Coastal Geomorphology

Global sea level has changed dramatically over the recent past, rising 100-150 meters since the end of the last ice age about 10,000 years ago, and continuing to rise today at a rate exceeding 1mm per year. Sea level change is a global environmental issue with many scientific and public policy aspects. The science issues are twofold. The first problem is that of understanding solid Earth processes and geodynamic properties that create tectonic motions at the locations of tide gauges, such as post-glacial rebound (creep in the mantle in response to the geologically recent melting of the northern hemisphere ice sheets) and determine the shape of marine basins. The other problem is that of understanding the influences of sea-level change on coastlines, through the analysis of coastal landforms and their change over time.

Global Volcanism

From the "Ring of Fire" around the Pacific to the Antilles arc in the Atlantic, volcanoes are part of the natural landscape, and offer opportunities to investigate some of the forces that both form or reshape the surface and present hazards to humanity. From a scientific perspective, it is important to understand the cycles of volcanic activity and the relationship between eruptions and landscape formation. There is both scientific and practical value in observing changes in volcanoes during the days, weeks, or months prior to an eruption, using available measurements of surface deformation, seismicity, and gas emissions. Observing transient signals is a challenging task, because only one fifth of the 600 or so active volcanoes on Earth are routinely monitored, even in the most rudimentary way. Space-based observations, including radar or lidar mapping of surface deformation, GPS arrays, remote sensing of gas plumes and surface temperature, offer the only practical means to monitor all active volcanoes. In conjunction with seismic and other *in situ* measurements, space-based observation provide a powerful tool to investigate the physics of magma migration, the role of gases and other fluids in volcanic processes, volcanic deposits and their mobilization, and eruptive cycles.

EXPECTED SCIENTIFIC ACHIEVEMENTS

Question 1: What are the motions of Earth's interior and what information can we infer about internal processes such as mantle convection and the generation of the Earth's magnetic field?

Expected new knowledge in the next 5 years

- Identification of regions where large temporal variability or trends exist in the Earth's gravity field as a result of mass redistribution in the solid earth, atmosphere and oceans;
- Order-of-magnitude improvement in the international geomagnetic reference field model;
- Order of magnitude improvement in knowledge of the Earth gravity field and International Terrestrial Reference Frame, to serve as a baseline for determination of the vertical motions of the Earth's crust and oceans.

Expected new knowledge in the next 10 years

- Identification of sources of gravity variations and relationship to mechanisms for mass redistribution among the hydrosphere, lithosphere, cryosphere, and atmosphere;
- Quantitative estimation of momentum exchanges between the Earth's interior, oceans, and atmosphere that result in variations of the earth rotation rate;
- Structure and dynamics of the Earth's mantle and core.

Question 2: How is the Earth's topographic surface being transformed and how can this knowledge be used to predict future changes?

Expected new knowledge in the next 5 years

- Local distribution of strain in deformation zones using interferometric SAR and geodetic techniques and relationship with increased vulnerability to earthquakes;
- Baseline global topographic dataset for identification of significant geologic features on kilometer-scale;
- Relationship between fine-scale geologic features and erosion, sedimentation, earthquakes, volcanic eruptions, landslides, and other hydrologic and biospheric surface processes;
- Baseline global record of volcanic processes including thermal activity, outgassing, and surface inflation/deflation.

Expected new knowledge in the next 10 years

- Global observation of surface deformation through several earthquake cycles and/or volcanic events and interpretation of these measurements in term of local stress in vulnerable regions;
- Relationship between sea level change and land subsidence for determining the trend and impact of sea level variations on global coastal zone environment;
- Decadal evolution of dynamic global geologic systems and relationship to vulnerability to natural hazards, including flooding, volcanoes, earthquakes, landslides, and coastal erosion.

6.3 NASA Program Elements

The most successful strategy to understand Earth’s dynamism and its relationship to the atmosphere, oceans, and other elements of the Earth system is an integrated approach in which process models are constrained by data acquired from traditional field and laboratory investigations, within the regional and global frameworks provided by airborne surveys and space-based observation. The NASA research strategy aims to achieve fundamental scientific advances through leadership in observing techniques and Earth system modeling, in cooperation with other national and international partner agencies and scientific institutions. NASA’s strengths and principal contributions to this interdisciplinary research effort are global observation of geologic processes and the topographic surface of the Earth, precise geodetic measurements to monitor the terrestrial reference frame, and measurements of the static and variable components of the Earth’s gravity and magnetic fields..

Characterizing the Earth's motions, both the bulk motion with reference to the stars and internal motions, calls for a combination of geodetic measurements. Geodesy is the science of measuring the figure of Earth, its rotational motions, crustal displacements, and gravity field. Determining the Earth's motion with reference to distant astronomical bodies (quasars) is principally achieved through Very Large Base Interferometry (VLBI) techniques based on simultaneous observation of quasi-stellar sources by an international network of radioastronomy observatories. The precise shape and time-dependent deformation of the Earth surface can be determined directly by space geodesy techniques, including Satellite Laser Ranging (SLR) and the Global Positioning System (GPS). Obviously, the motions of the Earth's interior cannot be measured directly and must be deduced from the analysis of surface deformations combined with high-precision space-based measurements of the Earth's gravity and magnetic fields.

Improved understanding of the impacts of solid Earth processes on human activities and societies, particularly in relation to assessment and mitigation of vulnerability to natural hazards, is part of NASA's strategic goals. Available observations of suitable accuracy extend over a few decades at most and cover only a very short period of the Earth history. For this reason, the research strategy aims to sample key geophysical and geological phenomena over appropriate time and space scales (e. g., study of earthquake cycles in the Los Angeles Basin), develop data analysis schemes that allow interpolating between sparse observation sites and relatively short data records, and create models that can simulate the range of possible future events. This strategy again relies on an integrative approach combining all previously acquired measurements and, at the same time, improving measurement techniques to unprecedented levels of accuracy and spatial coverage in order to foster new scientific discoveries. The principal advances realized in the recent past are the acquisition of the first global radar maps of the planet, using space-based synthetic-aperture radar (SAR) systems, and the development of interferometric SAR data analysis methods that allow reconstruction of surface topography and measurements of surface motions with unprecedented precision.

6.3.1 SPACE GEODESY AND THE INTERNATIONAL TERRESTRIAL REFERENCE FRAME

In this section, the discussion of space geodesy will focus specifically on the study of the Earth's rotation and deformation. Geodesy provides not only an accurate description of the Earth's motions, but also basic information for a broad range of fundamental investigations of oceans, ice sheets, and the Earth internal structure. For example, a measurement of sea-level rise at the level of precision (a few millimeters per year) now achievable by radar altimetry has no scientific significance unless the geodetic reference frame is known with the same accuracy.

NASA's pivotal role in geodesy and geodynamics has followed from the unique capabilities of the agency for extremely precise geometric measurements from space (NRC, 1990). Space-based geodesy, or simply "space geodesy", developed over the past four decades as a natural outgrowth of observations made to track the orbits of the first artificial satellites in the late 1950’s. Space geodesy now permits a determination of the Earth’s orientation in space, expressed in terms of nutation, precession, polar motion, and length of day with precision (on the order of 1mm) many orders of magnitude better than conventional geodetic techniques based on stellar astronomy and optical surveying. NASA’s space geodesy program includes Very Long Baseline Interferometry borrowed from radio-astronomy, precision satellite tracking based on satellite laser ranging, and positioning based on the radio-navigation Global Positioning System. Radar altimetry of the ocean surface and Synthetic Aperture Radar (SAR) interferometry are also utilized; the former is discussed in the Global Ocean Circulation and Sea Ice section of this plan (section 5.3.1), while SAR interferometry is discussed in the Global Geology section (6.3.4).

Space geodesy measurements provide unique and truly global diagnostics of the Earth’s fluid motions (oceans, atmosphere, mantle, and core) over a very broad range of time scales, from tidal to tectonic. Short-period (seasonal and interannual) signals are mainly associated with the atmospheric circulation. Changes in oceanic circulation and land hydrological processes (including snow and ice accumulation) can be detected on time scales from days to decades and beyond. Mantle convection, post-glacial rebound, and episodic violent phenomena such as earthquakes and volcanic eruptions produce signals on time scales from seconds to millions of years. Finally, material flow in the fluid outer core of the Earth and the relative motion of the solid inner core induce observable geodetic signatures at periods of a few years and longer. The key scientific problem is: *how effectively can the contributions from different processes in the Earth system be separated and, once separated, how can geodetic measurements be used to improve the understanding of each individual process?*

The challenge of geodesy is not only to make precise measurements of instantaneous positions but to also provide a stable reference frame against which to compare measurements such as sea level over decadal and longer time scales. The problem of fixing a reference frame is complicated by the forces both internal and external to the Earth which induce meter level changes in the location of the rotation poles, centimeter level changes in the center mass of the Earth and centimeter level motion of the land masses. NASA with other international partners supports the International Terrestrial Reference Frame (ITRF) project, organized under the aegis of the International Association of Geodesy, whose goal is to determine a global reference frame at the 1 millimeter accuracy level. NASA, in cooperation with the US Navy, is the principal contributor of precision observational data from its space geodetic networks, data archives and analysis centers, and provides technical and organizational leadership for the implementation of the project. The ITRF provides the data basis for investigating effects such as mantle convection, crust-mantle interaction, earthquake-related deformation, post-glacial rebound, dynamic ocean topography such as El Nino and the measurement of ice cap variability. The ITRF has also many practical uses: definition of a universal framework to which the operational Global Positioning System

(GPS) is connected, basic reference for the geographic coordinates used in land surveying, and precise orbit determination for satellite altimetry missions. The ITRF is determined from a few hundred reference points forming an irregular global network of non-uniform quality, providing daily determinations of the Earth's rotation parameters and annual estimates of deformation rates. Geodesists have recently noted that improvements in precise orbit determination and station positioning are slowing and we that the present technologies may be reaching a noise floor. Because scientific discovery in Earth science is predicated to a large extent upon improvements in positioning and timing accuracy, NASA's goal over the next decade is to advance space geodetic technologies with an eye toward millimeter or better positioning within an equally accurate and stable reference frame.

6.3.1.1 Systematic Geodetic Observation Programs

VLBI International Network

VLBI is the only technique capable of continuously determining the Earth's orientation and rotation rate (length of day) relative to inertial space. VLBI therefore provides the critical data to determine the long-period motion of the Earth's rotation pole and rotation rate and to provide long term stability for satellite orbits such as the GPS constellation or the LAGEOS geodetic satellites so important to the maintenance of the ITRF.

Because of VLBI's unique capabilities, NASA will continue to improve VLBI technology with the goal of higher precision and accuracy for the terrestrial reference frame. By the end of calendar year 2001, NASA and cooperating federal and international agencies will have completed a decadal program to improve VLBI observations using the Mark IV technology with a five fold improvement in sensitivity. The International VLBI Service (IVS) from its central bureau at the Goddard Space Flight Center provides the organizational framework for the international consortium of agencies participating in geodetic VLBI science. The IVS with NASA sponsorship has launched the CORE project (Continuous Observations of the Rotation of the Earth). CORE will engage over a dozen international partners in a program to use Internet and existing radio telescope facilities with the goal of achieving continuous operation of VLBI observations. In addition to more effective use of existing assets, CORE will demonstrate more cost-effective operation procedures and provide the required level of stability to enable monitoring Earth rotation over periods of several days. Beyond the year 2000, the main technical challenge will be the full automation of VLBI observations.

International Laser Ranging Service

SLR is the most accurate space geodetic technique available to measure the sub-decimeter scale motion of the Earth's center of mass. These displacements create a problem for global scale satellite altimeter missions such as TOPEX, Jason, and ICESat which cannot differentiate between a surface level change and a displacement of the Earth's center of mass. Sustained SLR observations of dedicated passive geodetic satellites like LAGEOS also provide essential information to determine the long-to-intermediate wavelength components of the Earth's gravity field and identify time-dependent gravity variations as envisaged in the forthcoming series of gravity mapping missions (see section 5.3.2). Individual range measurements from the best sites among a global network of nearly fifty SLR stations are accurate at sub-centimeter levels.

The Central Bureau for International Laser Ranging Service (ILRS), a service of the IUGG located at the

Goddard Space Flight Center coordinates and supports the efforts of numerous international SLR stations, and insures the quality of SLR observations and products. Continued development may reduce uncertainty below one millimeter over the next decade, but even more significant improvement would result from better geographical coverage of the globe. On a longer time scale (2003 and beyond), NASA plans to develop and deploy the SLR2000 equipment, a fully automated satellite ranging system capable of autonomously implementing a pre-programmed measurement sequence and reporting data over the Internet. The goal of SLR2000 is to provide more accurate orbit determination through better site location and continuous, cost effective tracking technology.

International GPS Service

GPS receivers are required for many practical purposes such as aircraft instrument landing, coastal navigation, surveying, etc. NASA's goal over the next decade is to provide technical leadership and organizational linkages with the international community that will enable the use of these receivers for scientific as well as practical purposes. To this effect, NASA sponsors the operation of the Central Bureau for the International GPS Service at the Jet Propulsion Laboratory (JPL), as well as related scientific methodology and software development. Daily orbit solutions produced at JPL for the GPS constellation are used to improve the accuracy of GPS fixes by thousands of public and private users every month. These improved orbits, in turn, allow the GPS constellation to serve as a reference frame for precise orbit determination for missions such as SRTM, Jason, TOPEX, VCL, ICESat, GRACE, CHAMP, and others. As discussed in section 5.3.4.3, permanent ground-based arrays of precision GPS receivers are currently being developed by NASA in cooperation with local agencies and governments for a variety of applications. Developments will be pursued to progressively improve automation, accuracy, and integration of these receiver arrays for increased scientific value. GPS software and antenna developments will also be required to reduce vertical positioning errors, which are still at least an order of magnitude larger than the theoretical limit. NASA is also supporting the development of GPS based remote sensing technologies that include limb sounding of the ionosphere and atmosphere and GPS reflection studies for geodetic imaging of the Earth's surface.

In 2001, NASA will release its newly developed Global Differential GPS system (GDGPS) capability that provides 10 to 20 centimeter real time positioning anywhere within the GPS constellation. We anticipate that this system will ultimately provide 1 cm real time orbit solutions. This new technology will enable a host of new civilian, commercial, and scientific applications from precision landing to onboard satellite processing. In the coming decade NASA intends to continue the development of advanced technologies to improve the GPS system capabilities and to utilize the system for remote sensing of the Earth system.

6.3.2 Gravity Field Studies

While local measurements of gravity have been made at the Earth's surface for more than a century, meaningful global gravity models could not be inferred until precision tracking of artificial satellites began in the 1950's. Since then, many successive generations of gravity field models have been produced, providing practical returns to the space program in term of orbit determination, and yielding new insights about the Earth's mass distribution and related forces which control mantle convection and plate tectonics.

Traditionally, the gravity field has been treated as a static property of the Earth, and scientific interest has been focused on the description of the field and interpretation of departures from the gravity of a rotating homogeneous fluid. The static field is dominated by irregularities in the solid Earth caused by convective processes that deform the solid Earth on time scales of thousands to millions of years. Further improvements in the accuracy of static field measurements, expected from forthcoming satellite missions, will resolve small-scale features of considerable geophysical significance, such as the depth of continental roots, the base of "hotspot" convection plumes in the mantle, and the detailed structure of tectonic features such as subduction zones and ocean ridges.

The most dramatic scientific advances expected from the next generation of gravity mapping missions will come from the investigation of the very small part of the field which does vary with time due to mass redistribution processes acting on time-scales from hours to thousands of years. These include tides raised by the Sun and Moon, post-glacial rebound, changes in ground water storage or accumulation over land (snow, ice, and water bodies), sea-level change and variations in ocean circulation. Much of this new information has applications to problems of considerable societal importance such as climate change and the availability of natural resources. Using variations in the Earth's gravity field as a remote sensing tool is now widely accepted (NRC, 1997).

6.3.2.1 Systematic Earth Gravity Mapping Program

Several decades of satellite tracking and sea surface topography data have been archived and used to deduce progressively more accurate global gravity field models. The most advanced model yet developed (by NASA and other federal agencies) relies heavily on satellite tracking data, as well as land and ocean surface measurements, and satellite radar altimetry. NASA generally relies on other agencies for surface gravity measurements. Airborne gravimeter and gravity gradiometer measurements complement satellite data and provide critical information for resolving the very short scales that are important for ice sheet mass balance studies, for characterization of tectonic features, and for closing gaps in satellite coverage at high latitudes. NASA will continue to support surface and airborne gravity measurements when relevant to support satellite missions.

New satellites, flying at various orbital inclinations and altitudes, continue to provide unique new information on the Earth gravity field which do not supersede, but rather supplement data from past missions. Thus, NASA will continue to acquire precision satellite tracking data, launch new laser reflector satellites in cooperation with international partners, and incorporate GPS receivers as standard flight instruments whenever convenient. Each new gravity model makes use of all previous data, plus new information derived from SLR tracking data and on-board GPS determination of satellite position.

6.3.2.2 Experimental Space-based Gravity Measurements

A new phase is beginning with a series of experimental gravity mapping missions. The CHAMP mission, led by Germany with US participation, is based on tracking a low-orbit spacecraft (CHAMP) using radio-navigation signals from a high-orbit satellite constellation (GPS), leading to further improvement in knowledge of the long-to-intermediate wavelength components of the gravity field. The NASA Gravity Recovery and Climate Experiment (GRACE) mission will pioneer a more accurate low Earth orbit (LEO-to-LEO) satellite-to-satellite microwave tracking technique (Launch scheduled for late 2001). The GRACE low-altitude orbit (450 to 250km) and expected five-year lifetime will provide unprecedented measurement accuracy for both the static and time-dependent components of the gravity field.

The anticipated scientific returns of these technical advances have been detailed in the recent *Satellite Gravity and the Geosphere* report of the National Research Council (NRC, 1997). Gravity measurements, as implemented by the GRACE mission, are expected to quantify any increase in the total mass of the ocean to an accuracy equivalent to 0.1 mm/yr sea-level rise, fully one order of magnitude better than the rate observed over the last century (on the order of 1mm/yr). Gravity measurements by these satellite missions will reduce uncertainty in the knowledge of the geoid to the same level as ocean altimetry measurements (approaching 10mm accuracy) for spatial scales of 300km and larger over land (see section 3.3.2). Beyond the determination of the static gravity field, the GRACE mission will explore the feasibility of detecting changes in the distribution of oceanic water masses, a space-based measurement equivalent to that of ocean bottom pressure. The GRACE mission is expected to detect, over a period of several weeks, transient changes in land water storage equivalent to the accumulation of a 10mm water layer over an area of 10^6 km^2, a promising development for the study of the global water cycle (see section 2.3.2). Thus, ultra-high precision gravity measurements open a pathway to systematic observation of time-dependent gravity as a remotely sensed property of Earth.

Follow-on experimental gravity mapping missions using laser interferometry for satellite-to-satellite ranging, high precision laser cooled gravity gradiometers, and advanced on board accelerometers could provide improvements of one hundred to one thousand times in the resolution of the time variable gravity component. This quest for improved sensitivity in gravity field measurement should lead to the measurement of seismo-tectonic events on the ocean floor and the dynamics of continental collision, as well as ultra precise measurement of fresh water distribution on the continent, precise measurement of ocean heating, and ice cap dynamics.

6.3.2.3 Space Geodesy Data Analysis and Modeling

Fundamental scientific advances are anticipated with the development of fluid dynamical models of the Earth's interior that are consistent space-based gravity and geodetic measurements and other (geodetic, seismic, magnetic) data. The analysis of gravity data combined with other observations relative to mass redistribution potentially provide a powerful means to monitor a broad set of variable phenomena in the Earth system. This task places an unusually strong demand on computational resources, and an important element of the research program will be the development of fast algorithms and data processing schemes to deal with the enormous data volume and complex relationships between measurements and the geophysical quantities of interest. As space geodesy data (gravity, center of mass, earth rotation, site displacements) are representative of the mass distribution, they offer a means to observe the denser components of the Earth system from space. It is expected that geodetic time series of Earth orientation (polar motion, length of day, center of mass) and time-dependent gravity field data will be combined with other measurements to monitor the ocean circulation, hydrology, and ice sheet mass balance. Most significantly, the fusion of temporal variablity of gravity over the oceans and polar ice caps coupled with high accuracy geodetic ocean and polar altimetry could be used to determine the steric or heat induced component of sea-level change to provide an accurate global assessment of the ocean’s heat storage role.

6.3.3 MAGNETIC FIELD STUDIES

The magnetic field seen at the surface of the earth or measured by a spacecraft in low earth orbit is the sum of the main field generated by fluid motions in the liquid core, by remnant and induced magnetism in the lithosphere, and external fields produced by currents in the ionosphere and magnetosphere. For this reason, magnetic field observations are of interest both to NASA’s Earth Science Enterprise and the Space Science Enterprise. The magnetic field and its temporal variations are a fundamental property of the planet and provide deep insight into the structure, composition and dynamic properties of Earth and its immediate surroundings. Through its own sponsored activities and collaboration with other national and international agencies, NASA leads the development of geomagnetic field models for scientific and practical applications. Space borne magnetic field measurements provide us with the enormously improved spatial and temporal resolution required for global geomagnetic field models. Of special interest are the time variable components of the geomagnetic field. From a solid Earth perspective, these time variable sources come from within the Earth's geomagnetic dynamo within the core, from electric currents induced in the mantle, lithosphere and oceans by external field activity, and from within the lithosphere due to variations in lithospheric stress and associated variations in conductivity.

A major objective of the geomagnetic field program is understanding the mechanism(s) in the Earth core that generate and maintain the main geomagnetic field and induce variations (including polarity reversals) over time scales ranging from years to thousands and millions of years. This fundamental problem relates to many unknowns: the nature of core-mantle coupling and boundary conditions, fluid flow in the outer core, and the detailed nature of 3-dimensional dynamo mechanisms. From the first observations of the secular variation of the geomagnetic field by Magsat in 1980 have come models of circulation within the Earth's molten core. The circulation models derived from these observations are now being compared to geodetic measurements of the Earth's rotation as well as surface deformation to understand previously unexplained phenomena. Magnetohydrodynamic models have only recently successfully modeled the self reversing phenomenon of the Earth's field and in the process suggested a higher rotation rate of the inner core than that of the Earth's mantle. In a dramatic statement for continued interdisciplinary modeling efforts, seismologists are debating the validity of seismic evidence supporting this inner core rotation anomaly. We have much to learn of the structure of own planet from studies of the geomagnetic field.

Of great interest to the surface change program are the smaller scale magnetic field variations that are associated with crustal magnetism. This anomalies and their time variations constitute a window for investigating the internal structure, composition and dynamics of the Earth's crust and mantle. Numerous laboratory and field measurements point to the possibility of geomagnetic and electromagnetic phenomena related to seismic events. Although we have yet to observe a significant level of reproducible results, geomagnetic field measurements including space based magnetotelluric experiments should be explored more vigorously because of the potential for significantly advancing our knowledge of earthquake and volcanic events.

6.3.3.1 Systematic Geomagnetic Observation Program

NASA undertook the pioneering POGO and MAGSAT missions which provided the first high-quality vector field measurements from space. Since the end of the MAGSAT mission in 1980, international partners have taken the lead for space-based magnetic measurements, with NASA's cooperation and support. Several upcoming missions, launched in 1999 and later years, will provide simultaneous observations from multiple spacecraft and allow improving the precision of magnetic field models. These missions include: Oersted (Denmark, February 1999), CHAMP (Germany, late 2000), and SAC-C (Argentina, late 2000). To complement this observational program, NASA maintains a magnetic modeling and analysis activity at the Goddard Space Flight Center, to provide processed field data to NASA investigators and scientific partners.

The primary observational requirement is continuous mapping of the geomagnetic field by satellites in configurations optimized to separate the various geophysical sources of the field. For example, external field studies are best served by measuring horizontal gradients at high altitude, while crustal field studies use vertical gradient data obtained from low altitude orbits. No single observing mission can satisfactorily discriminate between crustal, core-field, external field and electromagnetic induction, but each type of measurement contributes to advances made through combined analysis. Globally synoptic geomagnetic field measurements from a constellation of geomagnetic sensors could provide the improved separation of internal and external geomagnetic field sources required for lithospheric measurement and magnetelluric sounding. A key objective is to establish an orbiting array of accurate, high resolution vector magnetometers to measure both the external magnetic field and the related current systems.

We will continue to strive for a global constellation of geomagnetic instruments through the participation in international magnetic field monitoring programs. NASA will facilitate the placement of research-quality instruments on available flights of opportunity, as well as on dedicated joint missions with international partners whenever possible. Accurate, high resolution magnetometer systems are not presently suited to missions of opportunity due to their large mass, high power consumption and bulky designs. Technology development will be focused on non-magnetic star-tracker cameras for accurate attitude knowledge, miniature magnetometer arrays with adequate sensitivity and accuracy, and various electric field sensors. The availability of suitable measurement technology is currently limiting our measurement strategy.

6.3.3.2 Geomagnetic Data Analysis and Modeling

Numerical simulation of magneto-hydrodynamic activity in the Earth's core has been recognized as a grand challenge of physics throughout the 20th century, and some of these modeling efforts have been supported by the NASA program for high performance computation. Three-dimensional dynamo simulations have provided new insights into the Earth core dynamics, and will drive the development of better core field models. Improved methods for separating the crustal field will be developed, using synoptic satellite constellations, field gradient information, and refined models of the external field sources in the ionosphere and magnetosphere. NASA will continue to support further theoretical research and model developments, which are now beginning to generate realistic model fields with great promise from continued improvement.

6.3.4 GLOBAL GEOLOGY STUDIES

Global geology views the Earth landscapes as the outcome of many interacting processes involving the Earth's interior, surface hydrology, the biosphere and atmosphere. The NASA research program aims to develop fundamental understanding of these interconnected processes through the use of remote sensing data, field observations, and related data analysis and modeling activities. The program represents a natural springboard from which to launch application-oriented short-term studies focused on assessment of vulnerability to natural hazards such as floods, landslides and debris flows, coastal erosion, volcanic eruptions, and earthquakes. Fundamental understanding of landscape-forming processes is essential to reconstruct the history and evolution of dynamic geologic systems and thereby extend the time-frame far beyond the bounds of direct observation of contemporary phenomena. Detailed observations of the processes associated with natural hazards often exist only for a few decades, a time span much too short to encompass the range of hazardous events. Understanding the long-term behavior of natural systems is the pathway to assessing current risks of catastrophic events. Unraveling these interactions is a fundamental first step toward finding efficient ways to conduct human activities, taking into account available resources and potential hazards.

Tectonic Motion and Earthquakes

Local deformation and earthquake studies aim to understand and predict the behavior of earthquake fault systems. Intensive studies in areas such as the Los Angeles basin or the Tien Shan in China are conducted to deduce both the recurrence intervals and magnitudes of displacements along known faults, as well as measure and monitor the contemporary accumulation of strain. Buried faults are particularly challenging since they show no surface rupture and can only be inferred indirectly from geomorphic, stratigraphic, geopotential, and geodetic data. The principal NASA contribution is the measurement and interpretation of crustal deformation throughout the earthquake cycle (i. e., pre-seismic, seismic, and post-seismic periods) using space geodesy and remote sensing techniques, predominantly the Global Positioning System (GPS) and Synthetic Aperture Radar (SAR) Interferometry. These studies are usually performed in cooperation with other US and international organizations: the US Geological Survey, the National Science Foundation and many local agencies and organizations provide critical *in situ* observations and knowledge as part of various integrated research programs. A critical component to prediction of seismic phenomena is a more accurate knowledge of lithospheric rheology and stress. NASA provides the technological and scientific leadership in the development of space geodetic techniques to accurately map surface strain. We must now begin to focus our attention on new spacebased techniques to extend our knowledge of the state of the lithosphere.

Volcanism

Although volcanoes may lie dormant for centuries and become sites of intense human presence, they can erupt into catastrophic activity, sometimes on short notice. The problem is to identify the geologic properties and processes that govern the recurrence of volcanic eruptions, how eruptive events develop, and how past eruptions have affected the surrounding landscape. Many (perhaps most) volcanoes experience significant changes in the days, weeks or months prior to eruption, including surface strain, seismicity, ground temperatures, and gas emissions. Capturing these ephemeral signals can be challenging. Less than 20% of the 600 or so active volcanoes on earth are routinely observed. Systematic observation from space considerably enhances our capability to collect data that may be used to provide a long-term perspective on global volcanic activity. Remote sensing techniques provide only partial information that complements field data on the age, lava composition, sequence, and character of past eruptions, as well as structural aspects of likely eruptive sites. NASA's main contribution over the next decade will be precision geodetic and topographic measurements, gas emission studies, and thermal monitoring coupled with data interpretation and modeling to understand the processes that produce and accompany eruptions. These studies are conducted in cooperation with the US Geological Survey and other Federal Agencies, and combined with international efforts.

Dynamic Geomorphology

The landscape has evolved over geologic and shorter time scales to produce the topographic surface we see today. Land-forming processes are governed by differences in rock strength, moisture availability, vegetation patterns, and slopes created by tectonic motions. In addition to the tectonic and volcanic processes discussed above, a number of competing land-forming processes modify topography, including sedimentation and erosion by river systems, land subsidence, coastal erosion and landslides. These processes are modulated by, and affect other components of the Earth system, the atmosphere, hydrosphere, and biosphere. Orographic effects on the atmospheric flow funnel precipitation on the windward side of mountain ranges and create rain shadows on the leeward side. Both the nature and rates of dominant erosion processes are tied to topography and rainfall. Gently sloping, vegetation-covered landscapes will change at rates and through processes, such as soil creep, that are very different from the bedrock landslides and debris flows that erode steep, sparsely vegetated slopes. While *in situ* observations yield insight in individual processes, remote sensing provides a regional perspective to view large-scale processes and multiple process interactions, as well as a basis for comparing these phenomena in different environments. NASA programs provide unique measurement and modeling capabilities contributing to the understanding of topographic evolution and landscape development. These studies have important societal implications as they provide a scientific basis for quantifying vulnerability to natural hazards related to land-forming, as well as human impacts on landscapes.

Sea Level Rise

The geologic record reveals that mean sea-level has varied considerably in the past from its present day position. Over the last 1.6 million years, sea level fell and rose repeatedly in response to the waxing and waning of large continental ice sheets in North America and Eurasia. Sustained intervals of warmer climate were always associated with a rise in sea level, as the volume of glacier ice was reduced and the oceans underwent thermal expansion.

Potentially the largest impact on global mean sea-level would be from the melting of polar ice sheets. The scientific challenge is to assess the mass balance of very large polar ice bodies and factor in geological processes, such as eustatic adjustment in the underlying continental basis. Regional "post-glacial rebound" can be as large as 50-100cm per century at some locations in Scandinavia. At present, the combined uncertainty on trends in the mass balances of the Greenland and Antarctic ice sheets is larger than uncertainty in sea level rise from all other causes. Even partial shrinkage of the polar ice sheets would inundate the major coastlines of the world and produce serious economic consequences. On shorter time scales, the 10 cm rise currently being anticipated in the next 30 to 50 years will threaten coastal wetlands, increase exposure to storm surges and wave damage, produce increased coastal erosion and allow substantial encroachment of salt water in near-shore aquifers. Numerous cities built near the sea-shore in regions subject to geological subsidence are now very sensitive to further sea level rise. New Orleans in Louisiana is already below high-tide levels.

6.3.4.1 Systematic Global Topography Measurements

The principal new tools brought by space-based observation to the study of global geology are the capability to deduce surface composition over large geographic regions using multispectral imaging and the capability to produce precise, high-resolution, global topographic maps. The first type of information is provided by a suite of past and current moderate-to-high resolution multispectral imaging radiometers, such as the Thematic Mapper on the Landsat series, and similar visible and near infrared instruments on the French SPOT satellite series. For geologic applications, basic imaging data have already been acquired for most of the world and the main issue is one of data access.

Topography is a fundamental geophysical parameter. Precision topography is a key observable for global geological studies, other fundamental scientific investigations (e. g. geodynamics, hydrology, ecology) and a wide range of applications, including the assessment of coastal and river basin flooding, volcano and earthquake hazards. Topographic information can be obtained by stereographic analysis of optical image pairs (e. g. SPOT), but the most capable remote sensing method is the technique of SAR interferometry using synthetic aperture radar (SAR) data. The NASA Shuttle Radar Topography Mission (SRTM) is the first high-resolution (30m horizontal, 16m vertical) near-global topographic mapping mission with full consistency to the global ITRF geodetic reference frame.

SAR interferometry can also provide extremely high vertical (or line-of-sight) accuracy for studies of surface deformation, subsidence, volcanic inflation/deflation, etc. This technique for studying tectonic deformation provides unprecedented high-resolution and spatially continuous measurements, at sampling intervals of tens to hundreds of meters over large regions, that could not be obtained efficiently by any other method. Regional deformation studies, that require long sequences of SAR data from precisely known trajectories, are currently conducted with data sets from existing SAR satellites (European ERS-1 and 2 tandem missions, Japan's JERS, Canada's Radarsat). These systems were not optimized for interferometric observation, however, and suffer from a variety of artifacts and processing-related problems that preclude routine utilization over large areas.

The highest priority requirement of global geology research is maintaining repeated or (ideally) continuous space-based SAR observation of the surface of continents for systematic analysis of surface deformation and changes in topographic features. A minimum of ten years of measurements is necessary to study important time-dependent phenomena or "cycles", such as postulated for earthquakes. The objective is to maximize the probability of capturing significant phenomena and assess the spatial and temporal variability of deformation rate over a period long enough to cover at least one earthquake cycle. These measurements must normally be combined with GPS geodetic reference points and GPS array data to supply *in-situ* reference measurements and provide a continuous temporal perspective.

The second priority is conducting periodic (at least every five years) global topographic surveys at 30m spatial resolution and 2-5 meters vertical accuracy. This objective can be attained by the regular SAR interferometric surveys (see Box 10) complemented by discrete high-precision altimetric data provided by satellite-borne lidars (see Box 8 for the ICESat terrain mapping mission and section 1.3.1.3 for the experimental Vegetation Canopy Lidar mission). The objective of the NASA global geology program is to increase the spatial resolution of space borne lidar surveys to 3-5 meters across a relatively large swath, while achieving sub-meter vertical accuracy, to enable two-dimensional mapping of *ground* topography below the canopy for geologic structure, in flood plains and coast zones to estimate risk.

Box 10
Topography and Surface Change Mission

Solid Earth research and polar sciences give highest scientific value to repeated (systematic) synthetic-aperture radar (SAR) surveys of land and ice surfaces, and tandem SAR missions, for differential interferometric reconstruction of surface topography and surface deformation over intervals of days (ice streams) to weeks (active tectonic regions).

The technical requirements for the mission include:

- High spatial resolution (of order 10-30m) SAR imaging system with multiple polarization capability,
- Dual frequency (L-band + second frequency) or wide bandwidth (for split frequency analysis), optimized for repeat interferometric observations and minimal phase decorrelation by ionospheric, atmospheric, and surface phenomena.
- Capability to complete, every five years, a global topographic survey with 30m horizontal resolution and 2-5m vertical accuracy, in addition to high-resolution (1-10m) mapping of selected sites for process studies.

NASA is examining potential private sector investments in global SAR observation systems that could provide the required scientific information through a data purchase.

6.3.4.2 Experimental Geologic Mapping Missions

Basic geological, soil, and vegetation information is currently inferred from high-to-moderate resolution spaceborne optical imaging systems operating in the visible, near and short-wave infrared, as well as thermal infrared. A new generation of advanced imaging instruments on the EOS Terra, Landsat-7 and New Millennium Program EO-1 missions (see section 1.3.1.3) will provide valuable information to address geologic applications. The experimental ASTER instrument on EOS Terra will provide the first spectrally resolved thermal image data that will enable determining the composition of silicate materials, studying volcano temperature variations, and producing geologic and geomorphic maps. Owing to their high spatial resolution, ASTER thermal infrared image data are also expected to capture variable SO_2 plumes emitted by active volcanoes. Currently, no ASTER follow-on is planned after the five-year Terra mission but similar observation capabilities may be available from commercial systems when the usefulness of ASTER-like measurements for global geology studies is established.

The New Millennium Program EO-1 technology demonstration will provide the first spaceborne visible/near infrared hyperspectral imaging capability, enabling identification of most rock-forming minerals and surface materials based on spectral reflectance characteristics. While EO-1 coverage will be extremely limited, similar capabilities will also be available from two other hyperspectral imaging demonstration missions (NEMO and Warfighter) planned by the U.S. Navy and Air Force. Still another hyperspectral imaging satellite mission (ARIES) is planned by Australia.

Beyond these ongoing projects, NASA will encourage experimental or technology demonstration missions to explore innovative remote sensing approaches that can address outstanding global geology issues. In particular, NASA is studying options for a differential SAR interferometry demonstration mission that could be a pathfinder for sustained measurements of this type in the future (see Box 10). Another example is high-resolution multispectral imaging from geostationary platforms for continuous observation of transient gaseous emissions from active volcanoes.

NASA will encourage instrument concept studies and development to fully exploit the potential of satellite remote sensing for geologic mapping of the Earth surface. An active experimental airborne observation program is planned as a means to develop and test innovative remote sensing techniques, perform critical site-specific surveys, and validate space remote sensing data. Prominent among current aircraft sensors are the high-resolution hyperspectral Airborne Visible and Infra-Red Imaging Spectrometer (AVIRIS), in addition to thermal infrared imager, such as the MODIS and the MODIS/ASTER Airborne Simulator instruments (MAS and MASTER), and airborne imaging radar (AIRSAR) and Lidar systems for high-resolution topographic mapping.

6.3.4.3 Geologic Field Studies and Airborne Observation Campaigns

The NASA global geology program utilizes "natural laboratories" distributed over the whole world to observe and study specific processes and acquire validation data for verification of satellite measurements. For example, the western U.S. Cordilleras, the Himalayas including the Tibetan Plateau, and the high Andes mountain range in South America contain a wealth of information on the interplay between climate and tectonics. These areas are characterized by rapid crustal uplifts, high relief, and a variety of climatic regimes; geologic processes are recorded in the form of well-exposed rock units, complex alluvial fans and lake deposits amenable to satellite imaging. Southern California, the San Joaquin Valley, and the Tien Shan in China are characterized by high rates of deformation and complex earthquake fault systems. The Decade Volcanoes are so named by the geological community because they are the most probable sites of catastrophic eruptions in the next decade. The Pacific Rim region in general is particularly vulnerable to large volcanic eruption, strong earthquakes, coastal flooding and other geologic events. The East and South coasts of the US are characterized by rapidly changing coastal geomorphology caused by the interplay of subsidence, sea-level rise, increased urbanization pressure, and severe storm impacts.

These are examples of the areas where NASA will focus process studies and the deployment of airborne and *in situ* measurement facilities in support of future satellite observations. Airborne campaigns with instruments such as AVIRIS, MASTER, and AIRSAR will be conducted on a regular basis for scientific study purposes (annually in the U.S. and once every 3 to 5 years in other areas). The Pacific Rim I campaign, conducted for the first time in 1996, was a cooperative effort among eleven countries and dozens of international organizations. The project deployed the AIRSAR and the Thermal Infrared Multispectral Scanner (TIMS) instruments for studies of volcano, earthquake, and coastal process in Australia, New Zealand and Southeast Asia. A repeat Pacific Rim II campaign is planned in 2000, with an expanded participation and a possible follow-on in 2004. These provide critical data for understanding of geologic phenomena and the development of new observing techniques or algorithms that directly support the analysis, and integration of satellite observations.

In addition, *in situ* observing assets, such as GPS arrays, will be deployed as necessary for monitoring surface deformation over kilometer-scale baselines. Installation of the Southern California Integrated GPS Network (SCIGN) will be completed in 2001 and the network will be evaluated over a period of the next five years. Low-cost GPS arrays are currently being deployed at specific natural laboratories including some active volcanoes, tidal gauge sites in dynamic coastal environments, and other locations. GPS array data will be combined with Interferometric SAR data and other geological and geomorphologic information to understand the basic mechanics of subsidence, volcanism, and shallow earthquake ruptures.

6.3.4.4 Geologic Data Analysis and Modeling

Qualitative descriptions of the action of individual landscape-forming processes (e.g., the evolution of river systems) have been available for some time. More recently, with the influx of synoptic space-based observations, increasingly quantitative models are emerging (e. g., the fractal characteristics of river systems) that incorporate advances in fundamental understanding and provide a coherent basis for assessing the vulnerability to several types of disasters. Landslides triggered by events such as earthquakes, snow melt, or heavy rain are a very serious hazard in many areas. Recent progress in the development of quantitative modeling suggests that NASA offers a unique remote sensing capability to quantify triggered landslide events. Expected progress over a ten-year period, envisions the consolidation of such component models into a generalized model of dynamic geomorphology. While these advances will result mainly from combined research efforts in fundamental geological disciplines (e.g., age dating, petrology, etc.) supported by other funding agencies, any generalized model will also require global data derived from space observations for initialization and testing. Creating productive new methods to facilitate the analysis and interpretation of large data sets is a scientific priority for the next few years. More attention will be given to the development of integrative models capable of assimilating a diversity of *in situ* measurements, remote sensing observations, and laboratory data.

Tectonic models

Models describing the four dimensional variability of accumulated strain (deformation) are key to understanding earthquake source mechanisms. Such models must take into account the rheology (mechanical properties) of the geologic strata under diverse physical and chemical conditions. GPS arrays will provide the first continuous record of strain accumulation, which is the controlling parameter of earthquake frequency in active seismic areas such as southern California. Interferometric SAR observations can provide spatially contiguous data. Using such data acquired throughout the earthquake cycle, it is anticipated that computing strain accumulation in the crust will be possible. The medium-term (5-year) goal will be relating earthquake activity to global deformation patterns, which involves addressing the basic mechanisms of brittle-field deformation.

Volcanic models

Two important objectives are being pursued in volcanic process modeling: understanding how dormant volcanoes become active, and understanding the eruption process itself. The former type of model is needed to assess the vulnerability of several regions to volcanic hazard, some including large cities (e.g., Seattle). The latter is applicable to areas situated within striking distance of volcanoes, to simulate the outcome of potential eruptions. Resurgence of dormant volcanoes, such as Mt. Rainier, is not uncommon and could be extremely costly, given the size of the assets at risk. Such resurgence is the product of deep-seated magma mobilization beneath the volcano, manifested by changes in the local gravity field or topography, both of which can be monitored using space-based techniques. However, current knowledge of volcano resurgence is still tentative and a considerable cooperative effort with other interested agencies will be needed over the next 5 years to develop these models.

Dynamic geomorphology models

This category includes a broad set of models, encompassing diverse aspects of Earth System sciences, that are developed for hazard assessments. Data inputs include dynamic topography (using SAR and laser altimetry), and visible/infrared remote sensing. Coastal erosion and deposition models are intended for predicting the evolution of beaches and coastal wetlands, understanding vulnerability to storms and storm surges, and assessing the usefulness (or lack thereof) of palliative engineering methods. River system evolution models are needed to understand vulnerability to flooding in view of ever-changing land uses, erosion and deposition of sediments by streams. The research strategy over the next 5 to 10 years is to concentrate on the development of individual component models with the objective of integrating these components into future integrated Earth System models.

6.4 LINKAGES

Interagency linkages

NASA's Solid Earth program coordinates research and observational programs with many other US agencies, DOD, and industry. These partnerships are essential, as they provide the foundation for end-to-end research programs, from space flight project development and ground-based studies to data interpretation and modeling. For example, NASA is cooperating with NIMA for the development of the Shuttle Radar Topography Mission (SRTM) and is already generating terrain-related data and gravity field models for civilian and defense surveying applications. NASA is considering, with NOAA and FAA, the means to develop a space-based volcanic ash and SO_2 clouds monitoring program for the protection of air traffic, and is partnering with FEMA and the Army Corps of Engineers for floodplain mapping and modeling.

The proof-of-concept GPS-MET satellite project (1995), sponsored jointly with the National Science Foundation (NSF), demonstrated the capability of a NASA-developed GPS receiver to provide accurate atmospheric temperature and pressure profile measurements in a limb occultation mode. A recent development is the ground-based GPS monitoring of volcanoes; experimental deployment is underway at several sites. The realization and exploitation of the Southern California Integrated GPS Network is another example of a major joint activity with NSF, the US Geological Survey,the Southern California Earthquakes Center, and the Keck Foundation.

NASA will continue to cooperate with other agencies (notably the USGS) and international partners in the implementation of airborne magnetic field measurement campaigns to fill gaps in space-based observations and acquire ground truth data.

The EarthScope Initiative (www.earthscope.org) is an ambitious proposal of the solid Earth research community to significantly advance our understanding of the structure and dynamics of the North American lithosphere. The NSF, USGS and NASA are seeking the means to make EarthScope Initiative (www.earthscope.org) a reality. NASA has stated it's interest in supporting the Plate Boundary Observatory through it's on going geodynamics program and will provide the leadership for the development of an InSAR component.

The integrated wide area observations of both time continuous strain measurements of the GPS based PBO and the spatially continuous observations of the INSAR will make significant progress toward understanding the relationship between temporal and spatial variations in crustal strain and the associated risk of earthquake and volcanic eruption. Scientists have observed from continuous GPS arrays such as SCIGN previously unknown phenomena including silent earthquakes or unexpected changes in crustal deformation following earthquakes. Some of these forcings clearly come from water and/or temperature effects, but there is also evidence of tectonic process changes after large earthquakes (e.g. changes in velocity field after Landers). Earthscope will exploit recent advances in GPS and INSAR space geodetic technology to provide Earth scientists with an unprecedented view of crustal deformation and will undoubtly stimulate new insights in the workings of Earth's crust and advance the predicability of and the response to natural disasters.

International linkages

International cooperation is the normal mode of operation in Solid Earth Science. Over 60 international agreements formalize NASA's cooperative activities with other countries. NASA is the leading U.S. participant in international programs such as the International Earth Rotation Service, the International GPS Service (IGS), the Continuous Observation of the Rotation of Earth (CORE) program, the International VLBI Service, the International Laser Ranging Service (ILRS), and the International SAR Working Group.

6.5 REFERENCES

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CHAPTER 7

EARTH SYSTEM OBSERVATIONS AND MODELING

7.0 INTRODUCTION

The Earth science research agenda described in the previous chapters makes use of two broad classes of activities: observational and modeling. Continued progress in the study of the Earth as an integrated system requires their application and improvement so that aspects of the Earth system, or linkages among them, not addressed previously can be studied in detail. Further, it is critical that the observational and modeling activities be linked together, as observations that do not exist in the context of a model-based hypothesis can provide data but little insight, while models unconstrained by observations are frequently of little use in explaining the past or present, let alone for predicting the future. Thus, NASA's Earth science research planning places particular emphasis on maintaining a close linkage between observations and models so that the benefits of both sets of activities are maximized. A key method that is used for linking observations to models is model-based assimilation of heterogeneous observed data, described below. NASA is committed to development and application of model-based data assimilation, with particular emphasis on demonstrating, through assimilation, the value of spaced-based observing systems.

Observations are the important starting point for Earth science research. Several classes of observational activities are identified. First are the space-based measurements that form the largest part of NASA's program. As discussed earlier, major space missions fall into one of three categories: systematic, exploratory, and operational precursor. In addition, some space-based measurement activities exist mainly for purposes of technology demonstration; these are described in more detail in the ESE Technology Plan. The next category includes sub-orbital measurements, which include ground-, airborne-, and balloon-based observations. The sub-orbital measurements are carried out mostly for detailed study of Earth system processes, but some are designed for global characterization of environmental parameters and, in a small number of cases, for development of long-term data sets suitable for trend analysis. Laboratory measurements are carried out to characterize fundamental properties and processes. These observations and measurements both support the development of technology and algorithms for future sensors (sub-orbital and space-based) and provide the needed information for accurate representation of processes in models. Observations also are used to determine initial states for model predictions and to verify model predictions and simulations. Finally, it is important to recognize the linkage between different types of observations, especially in the context of the validation of space-based observations and the coordinated deployment of satellite, airborne, balloon-, and/or ground-based measurements in process-oriented field campaigns.

Mathematical models play several critical roles in Earth Science. First, they provide a framework for testing our understanding of the processes that govern the behavior of the Earth system and its individual components: the atmosphere, oceans, lithosphere, mantle, core, cryosphere, land hydrology, and biosphere. Second, they provide a means for simulating the observed changes in the Earth system and its components, including the effects of external forcings of the Earth system and internal interactions within the system to system responses. Such simulations can be focused on the present day Earth or can be applied retrospectively to simulate the prior evolution of the Earth system. They are especially useful for establishing consistency in our knowledge of the time evolution of planetary forcings, interactions, and corresponding Earth system responses. Third, they provide a method for predicting the future evolution of the Earth system and its components. When run in a prognostic mode, models calculate the time-dependent responses of the Earth system to a postulated set of time-dependent forcings. Multiple simulations with different assumed forcing functions or different representations of various processes allow the range of Earth system responses expected in the future to be explored. The results are important for assessing the sensitivities of the various components of the Earth system to future forcing and ultimately for evaluating environmental and other human-related impacts of future changes.

Finally, significant scientific advances arise from the combination of models and observations. Three significant ways in which they are combined include inverse modeling, data assimilation, and model/observation intercomparison. The first of these, inverse modeling, is useful when the forcing factors of interest cannot be unambiguously determined from independent sources and must be inferred instead from the known evolution of one or more components of the Earth system. Inverse modeling has been applied to a broad range of environmental problems, for example inferring sources and sinks of long-lived trace gases in the Earth's atmosphere. The second joint application of models and observations is data assimilation, a mathematical method whereby observed data are combined with model predictions to provide optimal, physically consistent, and geographically well-distributed fields of environmental parameters. These fields are used as input for diagnostic studies of Earth system changes and underlying mechanisms, for the initialization of numerical forecast procedures, for evaluation of model forecasts, for evaluating the usefulness of new observing systems in model simulations and predictions, and for determining needed improvements to the global observing network. They can also serve as a basis for trend analysis of Earth system variables when prepared in a consistent way over time. The third joint application of models and observations is model development and evaluation, especially in focused intercomparison studies in which the results of different model simulations are compared with corresponding observational data.

In general, a hallmark of NASA's Earth Science research strategy is ensuring close linkage between observation programs, data analysis, and predictive Earth system modeling at all relevant spatial and temporal scales. In particular, developing the means for full utilization of global observational data acquired by the agency (e. g. through systematic data assimilation) and analysis of discrepancies between observed and modeled fields is considered an essential component of the program, aiming to verify the scientific robustness of the models that encapsulate our knowledge of Earth system processes. In this respect, NASA's research strategy fully subscribes to the recommendation of the National Research Council/Board on Atmospheric Sciences and Climate (NRC, 1998) to: "Apply the discipline of forecasting… in order to advance knowledge, capabilities for prediction, and service to society". Synergy between global Earth observation, analysis, and modeling is perceived as an essential means to answer the following scientific questions and a specific contribution of NASA to the U. S. Global Change Research Program.

7.1 SCIENTIFIC QUESTIONS

To what extent can weather forecasting be improved by new global observations and advances in satellite data assimilation?

While weather prediction is the primary responsibility of operational agencies, such as NOAA in the US, scientific advances made in developing more accurate climate and/or Earth system models, as well as more effective methods for ingesting new types of observations, are directly applicable to the improvement of operational forecasting systems. Synergy between operational weather forecasting practice and the development of new observation systems or products is an effective engine of progress in both domains. The principal thrusts of ESE's cooperation with operational weather services are participation in the development of precursor operational instruments for application to various operational environmental satellite systems, development of new data products originating from space-based observing systems, and contribution to the development and experimentation of improved atmospheric circulation models and data assimilation schemes.

To what extent can transient climate variations be understood and predicted?

Extended-range weather forecasts (for periods from a season to a year) are of considerable value to businesses, resource management agencies, and farmers. Improved atmospheric circulation models and coupled ocean-atmosphere models have demonstrated predictability in weather patterns up to several months in advance for some regions of the world. Numerical simulations have also demonstrated the sensitivity of such predictions to a number of land surface and ocean circulation parameters. An essential condition for capitalizing on these scientific advances is access to the relevant geophysical information and the ability to ingest this information through more effective data assimilation methods. The information most useful for this application includes, in order of increasing persistence or "memory": *ocean surface winds*; *continental soil moisture*; *sea surface temperature*; *ocean sub-surface temperature and currents* (alternatively, *ocean surface topography*). Initial values of tropical ocean parameters are principally useful for ENSO prediction, while continent-scale soil moisture data are expected to significantly enhance the predictability of summertime precipitation over the interior of continents. Recent progress in seasonal prediction has come from realistic representation of mesoscale weather systems in coupled global atmosphere-ocean models (to be expected since the principal manifestations of transient climate anomalies are changes in storm track, frequency, and strength).

To what extent can long-term climatic trends be assessed or predicted?

The long-term prediction of potential changes in global climate is the most daunting challenge of all, because such predictions depend critically on accurate representation of all relevant "feedback processes" in the atmosphere, ocean, soil and ice, and the biosphere, as well as realistic guesses about future changes in primary forcing factors. Among the most critical problems are understanding the atmospheric processes that vertically redistribute energy, water and other constituents in the atmosphere; the relationship between cloud radiative properties and the underlying meteorological conditions; the partitioning of rain and snow among evaporation, storage and runoff; the effects of changes in land surface and land use on the latter; the exchanges of energy, fresh water, and trace constituents between the atmosphere and the ocean; the formation and evolution of sea ice; the influence of physical climate on biogeochemical cycles; and the trace gas composition of the atmosphere and response to changes atmospheric circulation. Building confidence in such predictions requires success in all four preceding steps in the science strategy. Another piece of information, that will eventually be needed for deterministic predictions of multi-decadal climate changes, is the initial state of the deep ocean circulation globally. Systematic observation of the global ocean circulation will be necessary for this purpose.

To what extent can future atmospheric chemical impacts be assessed?

Prediction of the evolution of atmospheric trace constituent composition is intimately linked to that of the meteorological conditions under which chemical and transport processes occur. The chemical constituent of greatest interest is ozone, which both protects the Earth from biologically damaging solar ultraviolet radiation, and is an active chemical agent pollutant that affects both plant and animal life. Ozone responds (for both production and destruction) to the concentration of many precursor species coming from both natural and anthropogenic sources. Accurate modeling of atmospheric composition requires knowing or forecasting the future evolution of these chemical forcings as well as relevant changes in climatic conditions. In the case of sufficiently large changes in atmospheric composition, interactions with resulting changes in atmospheric circulation and physical properties cannot be ignored (the chemistry of the polar stratosphere is an important case in point). Processes of particular importance for model assessments of potential atmospheric chemical composition impacts include the transport of material between the troposphere and stratosphere; the formation of aerosols and cloud particles and of their interactions with gas phase species; the natural variability in biological sources and sinks; and the balance between chemical removal and long-range tropospheric transport.

To what extent can future atmospheric concentrations of carbon dioxide and methane be predicted?

To predict future climate changes and global productivity patterns, it will be necessary to develop realistic projections of the atmospheric concentrations of carbon-containing gases such as carbon dioxide and methane. These projections require understanding the interactions between the biosphere and the physical environment (especially temperature, precipitation, and carbon dioxide concentration for the terrestrial biosphere; ocean circulation for the marine biosphere; and changes in nutrients for both), as well as the basic relationships between the physical environment, human management activities (e. g. land use, fishing), and biological activity. A combination of global observation of the biosphere (including vegetation cover, above-ground biomass, and the distribution of chlorophyll in the ocean) and global biosphere models will be needed.

In order to predict future atmospheric concentrations of carbon dioxide and methane, observations and representations of carbon cycling processes must be incorporated into terrestrial and oceanic ecological and biogeochemical models, as well as land cover change models. In addition, new and improved carbon cycle models will be necessary to calculate emissions for different landscapes, regions, oceans and the entire Earth system. Inverse modeling may be used to test our understanding of trace gas emissions in the light of observed atmospheric distributions and knowledge of carbon cycling processes. Such models will be important to assess our ability to simulate the past evolution of trace-gas concentrations and build up confidence in prediction capabilities for the future. The ESE will rely largely on information developed by NASA's partners in the USGCRP about future carbon dioxide emissions from fossil fuel combustion and methane emissions (e. g. from landfills, cattle, rice paddies, and natural gas production).

How is the Earth's surface being transformed and how can such information be used to predict future changes?

Recent advances in space geodesy make it possible to characterize land and ocean topography and it’s change to centimeter or better accuracy. This accuracy is sufficient to estimate the risk of flooding in river plains and coastal zones. Space geodesy enables us to follow the subtle effects of crustal deformation through the earthquake cycle, monitor the slow inflation of volcanoes and follow the subsidence of land from the pumping of wells. Though these geodetic technologies have been demonstrated, there is still much to do to achieve timely acquisition of space geodetic data with the required temporal and spatial resolution and to provide the necessary data analysis tools. Though we have the ability to monitor crustal deformation with great accuracy we have much to do in describing the physics of the earth's crust associated with violent earthquakes and volcanic eruptions. A thorough understanding of this physics is required to achieve reliable disaster forecasting . Space borne observations of the solid Earth whether they be measurement of gravity, geomagnetism , or Earth rotational dynamics provide the unique global perspective to better understand these forces which drive our restless earth.

Computer models are particularly useful to understanding solid Earth dynamics. Models transcend the limitations of time and space by simulating the entire earthquake cycle over thousands of years and span complete fault systems to provide a better understanding of how earthquakes occur and how faults interact. Complex three-dimensional models with millions of unknowns are required to adequately model regional tectonic systems. High performance computing has recently passed the milestone of replicating a self reversing magneto hydrodynamic geodynamo with the suggestion of a differential higher rotation rate for the inner core – a model derived observation that has stimulated the interest of seismologists. Three dimensional models for mantle convection based upon observation can be played forward to describe the evolution of the Earth's outer layers. As we approach realistic models for the internal dynamics of the Earth, we gain new insight into the powerful forces which shape the Earth's surface.

7.2 OBSERVATIONS

As noted in the introduction, the observational approaches used in ESE programs include space-based measurements, sub-orbital measurements using ground-, airborne-, and balloon sensors and laboratory-based investigations of basic physical or chemical properties relevant to remote sensing methods.

7.2.1 Satellite Observations

From both programmatic and scientific strategy perspectives, the NASA flight missions program distinguishes three basic types of missions– exploratory scientific missions, systematic scientific observation missions, and operational precursor and technology demonstration missions. These categories were first introduced in the "post-2002 mission scenario" developed in 1998-99 by soliciting specific research questions and associated measurement concepts from the science community, and integrating them into a slate of mission concepts reviewed by representatives of this broad community. The identification of three categories of satellite missions represents a significant departure from the prior programmatic outlook of the Office of Earth Science. The original architecture of the Earth Observing System attempted to combine all three types of missions: a series of three identical platforms were to be flown successively, carrying the same complex instrument payloads designed to study processes, provide long-term continuity of measurement, and demonstrate innovative measurement techniques that could be transitioned to operational partners. Under the current approach, a determination needs to be made early in the planning cycle concerning the specific purpose and category of each mission. The basic characteristics of these three mission categories were defined in the Overview (section 3.2) and are summarized briefly below.

Systematic Measurement Missions

The systematic measurement program is designed to provide consistent time-series of observations of the key environmental parameters that best characterize the natural and forced variations of the total Earth system and changes in relevant forcing factors. The goal of ESE is to define a limited set of parameters for systematic measurement that includes only enough parameters to characterize the key independent forcing and response factors that cannot be inferred from measurements of other parameters based on knowledge of the processes that connect them. To this end, it is critical that systematic measurements include those of parameters governing the physical, chemical, and biological state of the Earth system along with external forcing factors. Within a given category, the list of systematic measurements will typically not include parameters that can be calculated unambiguously from one or several parameters that are observed. For example, it is desirable to reduce the number of chemical constituents that must be observed systematically, but not so much that the number of truly independent basic physical state parameters is reduced. As another example, global precipitation must be observed systematically because it cannot yet be precisely inferred from systematically observed meteorological parameters such as temperature and moisture.

The intent is to acquire long enough records, with the required sampling density and measurement accuracy, to characterize specific Earth system variations and their causes. The systematic measurement missions typically build on existing observation methods and aim for consistency with previous measurement series. While new systematic observation missions may take advantage of improved measurement techniques, the continuity objective usually implies that technological innovation will be restricted to incremental changes, driven more by the need for reduced cost than performance upgrade. (It is important to note that technology improvements may be made through technology-oriented missions, such as the New Millennium Program described in the ESE Technology Plan.) Whenever possible, NASA will seek to leverage the related global measurement programs of national and

international environmental agencies that are mandated to deliver operational services, and/or acquire the data needed to achieve its scientific research objectives from commercial information providers.
Systematic measurement is not synonymous with continuous measurement, although the simplest way to assure systematic measurements is to have a continuous series of measurements, ideally with adequate overlap between successive sensors that questions about inter-instrument differences can be answered. The strongest requirement for continuity (overlapping measurement records) between successive measurement series occurs when the variability in a given parameter is small relative to the ability to provide accurate calibration for a satellite sensor, either in terms of pre-launch laboratory calibration or, where appropriate, through comparison with closely related ground-based or in situ observations. Thus, for example, total solar irradiance (TSI) is a parameter for which the overlap requirement is extremely important, given the small variability in TSI and the difficulty in assuring exact calibration of radiometric sensors in space. On the other hand, when a geophysical signal is varying relatively slowly and sensors can be well calibrated, gaps between successive measurements may be acceptable. For example, Synthetic Aperture Radar (SAR) mapping of the major continental ice sheets only needs to be done about every five years to check for major changes in the ice shelves.

The maintenance of a stable and accurate terrestrial reference frame is an example of a systematic measurement which must be made over decadal time scales. How do we measure the millimeter per year change in sea level or ice volume when everything on Earth is moving- even the continents? The terrestrial reference frame captures the Earth's constantly changing shape change over time to allow for the comparison of physical measurements of Earth over decadal time scales. NASA developed the space geodetic techniques that now serve as the supporting measurements for maintenance of the terrestrial reference frame. The terrestrial reference frame enables satellites to navigate with centimeter precision providing clear images of the El Nino and La Nina, revealing the first complete measurement of the global ocean floor, allowing the comparison of millimeter scale sealevel rise over decadal time scales. Society is becoming increasingly dependent upon the terrestrial reference frame for the long term registration of data within geographic information systems (GIS), land surveying , timing, and other similar civilian applications. Discovery has been enabled by the continuing improvement in the accuracy of the terrestrial reference frame by nearly a factor of one thousand over the past thirty years.

In general, the ESE plans for continuity of key systematic measurements, with the understanding that gaps or discontinuities may occur in the case of premature failure of a sensor or spacecraft. The ESE plan does not provide for instantaneous (in-orbit) replacement of systematic measurement missions. However, through close interactions with its domestic and/or foreign partners (including participation in pre-launch calibration, algorithm intercomparison, etc.), contingency dispositions can be made to complete a measurement record with data from non-NASA assets, should a gap develop in a systematic measurement series. A significant component of the ESE scientific research program is the development of integrated, long-term, multi-sensor/multi-platform data sets for environmental parameters will be particularly useful in such cases, as well as the more typical cases of transition from one sensor to its replacement. Such contingency measures have, in fact, been a long-term feature of the ESE program applied to data sets as diverse as the total ozone from the Total Ozone Mapping Spectrometer and Solar Backscatter Ultra-Violet instruments, or sea surface temperature from the Advanced Very High Resolution Radiometer data and ship or buoy measurements.

Exploratory Satellite Missions

Exploratory missions are focused on scientific discovery and are designed to acquire new or dramatically improved global-scale measurements and to yield new or deeper insight on a specific component or process of the Earth system. The intent is that each exploratory satellite project should be a one-time mission that would deliver conclusive scientific results concerning a focused set of scientific questions. In some cases, this may involve measurement of several related parameters so that closure tests may be carried out (as has frequently been the case in the past in atmospheric chemistry measurements, in which simultaneous observations of long-lived source gases, reservoir species, and free radicals are made), while in others it may involve a pioneering measurement of one or a small number of new environmental properties (such as will be the case with the upcoming GRACE mission, in which the spatial and temporal variation of the Earth's gravitational field will be mapped with unprecedented accuracy).

No commitment for long-term measurement is made with this class of mission, although it is possible that the results of an exploratory project could result in the recognition that it would be beneficial for scientific and/or operational purposes to initiate a continued observational program to fulfill the scientific objectives of the ESE. For example, the success of the space-based precipitation measurements made with the TRMM satellite have led to a proposed project to undertake systematic measurements of global precipitation in the future, in conformity with the original plan for the EOS program.

The guiding principle for the exploratory satellite program is the promotion of new scientific ideas and technical innovations. For this reason, the exploratory satellite program cannot be rigidly planned: successive flight projects will be chosen on the basis of periodic calls for proposals and a selection process involving peer review. The solicitations for exploratory satellite missions will indicate those scientific questions of greatest interest at any given time but will allow for possible selection of a mission addressing any scientific question if that mission best meets the criteria established in the Overview, Section 2.1. In particular, the ESE needs to allow for the possibility that advances in technology may enable a new class of measurement not previously possible. It is essential that the selection process for exploratory missions have sufficient flexibility to undertake promising new measurements.

Operational Precursor and Technology Demonstration Missions

The ESE recognizes that requirements for ever more comprehensive and accurate measurements place increasing pressure on environmental agencies and require major upgrades of existing operational observing systems. In order to enable such advances, NASA will invest in innovative sensor technologies and make available more cost-effective versions of its pioneer scientific instruments, such as can be used effectively by operational agencies or commercial operators. The Implementation Plan identifies several operational precursor or "bridging" missions that will lead to future operational deployment in low Earth orbit or geostationary orbit during the next decade, principally within the framework of the NPOESS and GOES programs. Active participation of operational user agencies or partners is essential in the definition and development of these new observing systems and their transition to operational deployment. The currently planned NPOESS Preparatory Project (NPP) is a particular example, as it will not only provide early flight opportunity for two instruments selected by NPOESS but also provide the first flight of the Advanced Technology Microwave Sounder (ATMS) instrument being built by NASA.

The primary objective of technology demonstration missions is to promote and validate breakthrough technical innovations in new sensor concepts and spacecraft components. Technology demonstration missions may also constitute a major first step toward the realization of future operational instruments that may be deployed as part of operational observing systems (e. g. high-resolution land cover imaging radiometer; geostationary atmospheric sounder). Technology demonstration missions are normally conducted under NASA's New Millennium program and are part of the ESE technology program that parallels the scientific research program.

The first operational precursor mission likely to be implemented is one for the direct determination of tropospheric winds. Other potential missions which have been identified in this category include lightning detection from a geostationary platform (Lightning measurements have been demonstrated from low earth orbiting platforms, but not from a higher altitude platform that provides the opportunity for better temporal sampling than the twice a day measurements available from low earth orbit.); high resolution gravity change measurement to track the movement of water from the ocean to land or ice cap; high spatial resolution, steerable, multi-spectral imaging for use in geostationary orbit for focused observation of rapidly-evolving events or phenomena (“special events imager”); and improved geostationary soundings of the temperature and humidity of the atmosphere (first being tested through the New Millennium Program via its selection of the Geostationary Infrared Fourier Transform Spectrometer (GIFTS) instrument for launch in 2003).

7.2.2 Sub-orbital Observations

The ESE recognizes that a coherent Earth science research strategy must combine findings from global observations with insight gained from specialized studies, especially *in situ* measurements or airborne remote sensing at much higher spatial and temporal resolutions than currently possible from space. Sub-orbital observations supported by the Earth Science Enterprise are largely of four types – ground-based, oceanic, airborne, and balloon-borne. These are used for a variety of purposes, including detailed process-level understanding, calibration and validation of space observations, proving the feasibility of measurement approaches designed for new types of space-based observations, and in a limited number of cases providing information on long-term trends (e. g. aerosol optical depth data from atmospheric transmission measurements). The ways in which sub-orbital measurements contribute to studies of the different components of the Earth system and linkages between have been described in the previous chapters, but it is helpful to review the contributions which they make to the ESE program.

The sub-orbital measurements contribute unique scientific information in several areas. The surface-based observing programs of Federal agency partners in the USGCRP are especially important for the advancement of Earth system science. Examples include NOAA’s TOGA array of ocean buoys that complement satellite altimetry in observing ENSO events, DOE’s Atmospheric Radiation Measurement (ARM) program complementing satellite measurements of radiation transfer in the Earth’s atmosphere, and DOE’s Ameriflux network of towers whose carbon dioxide flux measurements are useful to validate space based measurements of primary productivity (e.g., NDVI).

Ground-Truth and Comprehensive Process Observations

In situ and remote sensing measurements made at the surface of the Earth, in the ocean, or in the atmosphere provide "ground truth" against which space-based measurements are compared. They also help strengthen our knowledge of processes through comprehensive characterization of active sites or specific regions at a given time, which is not usually possible with remote sensing techniques. This is particularly true of measurements in the area of chemistry, radiation, and biology. The large number of chemical species whose concentrations are related by photochemical, transport, and microphysical processes (and are needed if quantitative tests of chemical mechanism sets are to be carried out) cannot typically be observed from satellites, and in situ observations (most typically made from airborne platforms) provide the completeness necessary for such tests. For atmospheric radiation studies, such measurements that may include information on the concentration of aerosol and cloud precursors, the physical and chemical properties of aerosol and cloud particles, and measurements of the radiation field which is strongly affected by the presence of particles. In biological studies, observations may include detailed characterizations of the distribution and availability of the chemical nutrients necessary for supporting organisms, of the range of biological species present at a site, and of the transfer of material between organisms and the environment.

These comprehensive data sets can form the basis for critical tests of models used to represent key physical, chemical, and biological processes. These “process models” can be applied to a range of geophysical conditions and can also be included in global models, either directly or in parameterized form. The role of process models is described in section 7.2.1 below. These ground-based observations can also help identify "surrogate measurements" that can be made globally through space-based remote sensing techniques.

Time Resolution

Sub-orbital measurements may allow for intensive sampling in the temporal domain, ranging from the resolution of diurnal variations (not possible from space-based observation in low earth orbit), to the characterization of seasonal and interannual variability at a limited number of sites. They can also provide continuous measurements under a range of conditions, including observation of surface parameters in unfavorable (e. g. rainy or cloudy) weather that can block space-based remote sensing. The temporal sampling can be particularly important for those parameters that are significantly affected by clouds, such as those involving the surface radiation budget and the surface flux of UV radiation. Without such temporal sampling, it can be difficult to determine diurnally averaged quantities given the large variability that clouds can introduce and the limited temporal sampling of most space-based systems, i.e., those in low Earth orbit.

Spatial Sampling

In situ and surface-based remote sensing techniques may provide capability for vertical sampling not possible from space. These include probing the detailed vertical structure of the lower atmosphere, the oceans, soils, vegetation canopies, and ice. Detailed vertical resolution not only provides process-level information but also constrains and tests algorithms used in remote sensing observations. An example of the latter is the use of shallow ice probes on ice sheets to evaluate the relationship between snow accumulation rates and space or aircraft-based microwave measurements.
In situ sampling also can provide information about the detailed spatial (both horizontal and vertical) variability that is averaged over in many remote sensing observations. This is a particular problem with atmospheric limb sounding, which involves a very long measurement pathlength through the atmosphere. Any inhomogeneity in the composition of the air masses viewed by the sensor can complicate the interpretation of the satellite observations. Such inhomogeneities can arise in particular when the atmospheric ray path cuts across strong gradients or encounters the presence of clouds or aerosols in part of the field of view. Sub-orbital measurements that are made coincident with such satellite observations can be very useful in aiding the interpretation of the space-based measurements. *In situ* sampling can also characterize spatial heterogeneity in surface properties that occurs at scales finer than the spatial resolution of surface images (i.e., sub-pixel variability).

Calibration Consistency

Sub-orbital measurements allow the possibility for assuring consistency of calibration over time because accurate laboratory calibrations can be performed either during the measurement sequence for ground-based sensors or for both pre- and post-flight for aircraft- and balloon-based sensors. This contrasts with the calibration possibilities for space-based measurements from free-flying satellites, for which laboratory-based comparisons with fixed standards are only possible before launch.

7.2.3 LABORATORY AND/OR PROCESS MEASUREMENTS

The intellectual capital for both the planning and exploitation of Earth system observations is vested in an active research and analysis program. The ESE research and analysis program is conducted along both traditional discipline lines and selected interdisciplinary themes. It includes activities driven by current Earth science questions as well as opportunities to exploit the data from specific observing systems. The

ESE research and analysis program is strongly focused on Earth System Science, has defined the Earth System Science issues identified in preceding chapters, has developed strategies to bring fundamental Earth science research to bear on these issues, and has laid the interdisciplinary groundwork for the modeling activities described below.

While the physical, chemical, and biological laws that underpin Earth system phenomena are well known for the most part, there are needs for specialized theoretical or laboratory investigations to strengthen the existing knowledge for quantitative modeling and the formulation of algorithms that relate the desired environmental properties to remote sensing data. Furthermore, remote sensing techniques often rely on very specific and still insufficiently determined properties of electromagnetic signals observable from space. Specialized laboratory measurements are needed, for example, to determine with needed accuracy molecular and particle optical properties, chemical reaction rates, reflectance, emittance, and scattering properties of surface materials, and metabolic rates of organisms under various environmental conditions. The results of such focused laboratory measurements frequently comprise critical input into process-level models that are used to represent the detailed operation of processes in the environment.

7.2.4 Observation Inter-comparison, Validation and Integration

The different types of observations available through the Earth Observing System are frequently used in a coordinated way and typically involve pairing of satellite-based and sub-orbital observations. The two main reasons for this are (1) the validation of space-based sensors and (2) the joint application in field campaigns in which the "top down" and typically larger-scale observations from space-based sensors are combined with higher spatial resolution and more comprehensive observations available from ground-based or in situ platforms.

Satellite validation can involve both surface-based and airborne measurements. The most straightforward approach to validation is to compare the results of measurements of the same quantity made concurrently by different methods to see if they agree within their respective known errors. Where widely distributed ground-based networks are available, such comparisons can provide a good first-order check of new sensors as well as an objective test of the differences between related satellite instruments. In many cases, comparisons of this sort are conducted using operational networks of other organizations. For example, total ozone observations are typically compared with total ozone measurements from the International Dobson network, while ozone vertical profile measurements are compared with corresponding measurements from the international ozonesonde network (both those networks are coordinated through the World Meteorological Organization's Global Atmosphere Watch program). Similarly, ocean altimetry measurements are compared with sea-level measurements from precision tide gauges. Other measurements may be compared more directly with NASA-provided ground-based instruments; examples of networks used at least in part in this way include the Network for Detection of Stratospheric Change (NDSC), used for comparison with space-based atmospheric chemistry measurements, and the Aeronet network, used for comparison with space-based atmospheric radiation and aerosol studies.

Another type of validation is the direct comparison of space-based and airborne measurements. Such comparisons are of particular interest when new remote sensing observations are made for the first time and comparison with observations from similar airborne instruments with substantial heritage can provide confirmation of the operation of the space-based sensor. The validation of the TRMM precipitation radar measurements using airborne radar is such an example. In a number of cases, dedicated airborne simulators of space-based instruments are constructed and used to establish significant experimental heritage prior to the flight of the space-based sensor. Airborne simulators have been built for several EOS instruments, notably MODIS, MOPITT, and MISR; these airborne simulators have been widely used within the ESE airborne observation program for a range of environmental studies.

Most process-oriented ESE field campaigns make active use of space and sub-orbital measurements. The space-based measurements frequently provide the wider spatial context for the more focused (and geographically localized) surface-based and/or airborne observations. The comprehensive measurement capability available from surface-based and/or airborne observations complements the broader spatial picture (but typically more limited parameter suite) observable from space. Thus, field campaigns in various areas, such as BOREAS, LBA, and the various FIRE campaigns, were all planned from inception to combine surface-based, airborne, and space-based sensors.

Finally, it is worth noting that as new surface-based and airborne measurement capabilities become available, it is frequently necessary to carry out detailed intercomparison of related measurement techniques. This is particularly important in those cases where different measurement techniques obtain different values for what should be the same quantity. An example of this has been the past inconsistency in measurement of total odd nitrogen in the upper troposphere, for which multiple instruments have been flown side-by-side on aircraft to help characterize the nature of the inter-instrument differences. Such intercomparisons will be made in the future as circumstances demand.

7.3 EARTH SYSTEM MODELING

The development of models that can simulate the full Earth system, including the key processes that link the different components is the ultimate aim of the modeling component of the Earth Science Enterprise. Such fully interactive models can only be developed through the linkage of less ambitious models that simulate individual components of the Earth system and critical coupling processes. Thus, the ESE modeling strategy is to build up from focused process models that are designed to simulate some particular mechanism in great detail, through component models that simulate the behavior of a major component of the Earth system, to interactive multi-component models that simulate the coupled behavior of two or more components of the whole system. Process and component modeling efforts need to be balanced by larger scale modeling efforts focused on linkages and coupling between several components. Models can be used in a diagnostic way as a test of our understanding, based on observations and a view of how the system works. They can indicate gaps in observational data and help identify critical variables requiring better characterization. Models also can be prognostic, or predictive, and assist in guiding future actions or policies.

Although the focus of the modeling effort is on the science associated with the conception and evaluation of models, significant technical challenges also exist associated with the development of numerical codes and the exploitation of the models. The extreme demands placed on high-end computing by long-range climate simulations with state-of-the-art atmosphere-ocean-land models cannot be met by faster and more powerful computer equipment alone. Corresponding investments are needed in numerical analysis, development of faster model codes, and implementation of faster application software, optimized for running on the massively parallel supercomputer systems that are likely to become prevalent in the future. On the other hand, it is clear the such model code optimization places a significant burden on the groups developing such models, and a balance needs to be struck between optimization of codes for specific machines and developing the software tools and hardware that will allow for the relatively easy use of existing and newly developed codes in a variety of computational environments.

In other areas, significant challenges associated with data availability limit model advancement. In particular, ecological models, coupled surface-atmosphere models, and biogeochemical cycling models are most limited currently by the availability of quantitative, accurate measures of the entire global land and ocean surface for their initialization and testing. Satellite data provide the only feasible alternative when consistent complete global measures of surface properties are required. In some cases, these models are also severely limited by current understanding of key ecological processes (e.g., carbon allocation, root function, ecological disturbance). Thus, research to advance total Earth system modeling must proceed along a number of fronts simultaneously: increasing computational capability and software optimization, developing and improving observational data sets, and improving our understanding of controlling processes and how to effectively portray them in models.

NASA is interacting closely with modeling efforts in other federal agencies, notably the Department of Energy and the National Science Foundation to help promote the development of computer hardware and software, as well as the specific modeling frameworks and algorithms, that will together enable the enhancement of modeling capability. Close involvement of ESE in NASA’s High Performance Computing and Communications (HPCC) initiative is an important element of NASA’s strategy for advancing the state of Earth system modeling.

7.3.1 Process Models

Process models are designed to provide detailed representations of physical, chemical, or biological processes that occur within the Earth's system. These models are typically developed with full knowledge of the findings of process-oriented observational campaigns, especially studies based on comprehensive analyses of frequent, high resolution measurements of a large number of parameters. The existence of a comprehensive set of observations together with the development of a model based on well-defined physical, chemical, or biological processes provides a strict test of one’s understanding of these processes. A model that accurately represents a large number of related quantities is more effectively constrained by observations, can be more thoroughly tested, and is more likely to be correct than "simple models" which simulate only a limited set of observables.
Realistic process models, carefully evaluated through comparison with independent observations, provide critical tests of our understanding of specific environmental processes and can be used for a range of environmental conditions. Applied in this way, they can predict observational parameters that can then be quantitatively tested through additional observations. Such models can thus provide guidance for the conduct of observational programs and help in identifying spatial or temporal regions of disagreement between theory and observations. When disagreement is found, consideration of the observed discrepancies helps focus further research efforts on related conceptual issues and observable parameters.

Process models, because they attempt to account for as much detail of a process as possible, are frequently very complex and computationally demanding, and thus are not usually well suited for direct use in global models of the Earth system or its components. In such cases, parameterizations of process behavior are developed so that the important biological, chemical, and physical processes can be represented in the global models with the computationally daunting details omitted. The parameterizations are typically tested through comparison with process models and then applied in larger-scale models. Process models applied to limited regions can also be nested within larger-scale parameterized models.

Examples of process models and associated simpler parameterizations abound in Earth science.; Several such process models are referred to in the relevant sections of the preceding chapters. e. g. with reference to the heterogeneous chemistry that takes place on aerosol and cloud particles in the stratosphere, the formation of cloud particles in convective systems in the atmosphere, etc. In all cases, detailed process models are developed on the basis of chemical, biological, and physical principles and tested by comparison with comprehensive observations made in airborne campaigns. The development of corresponding parameterizations that can be quantitatively evaluated through comparison with large-scale and global observations is an essential complement to process modeling.

7.3.2 Component Models

Model development is frequently initiated by focusing on the dynamics of one component of the Earth system, while the roles of the other components are held fixed or otherwise specified as a time-dependent external boundary conditions or "forcings". These component models frequently correspond to the subjects of traditional Earth science disciplines: meteorology, atmospheric chemistry, oceanography, ecology, solid earth, etc. Models in this category may be used to simulate the present, past, and future evolution of an Earth system component, although assumptions must be made about the effect of changes in other interacting components of the total system. By focusing on a single component, such models necessarily ignore or overly simplify the interactions and feedback processes that may exist with other components. On the other hand, single component models provide a means to very carefully describe that component and to focus computational resources for higher spatial and temporal resolution, or for more detailed representation of operative processes, than would be possible in a more comprehensive model.

Numerous examples of component model applications are given in the previous chapters. For example, atmospheric general circulation models that use specified sea surface temperature fields provide important information on atmospheric evolution over a wide range of time scales, including response to seasonal, interannual and longer-term ocean temperature anomalies. However, such atmospheric models clearly cannot represent the critical feedback loop between the atmospheric and oceanic circulations. Similarly, models of ocean biology may include an assumed flux of nutrient substances from the atmosphere but cannot represent the actual variations in this flux caused by changes in meteorological or conditions; therefore they might miss an important source of biogeochemical variability. It is important that the limits inherent in the use of single-component models that are not coupled with the other components of the Earth system be fully recognized in drawing conclusions from the results of such model simulations.

7.3.3 Model Integration Strategy

The development of interactively coupled models that realistically link different components of the Earth system is one of the most important goals of NASA's Earth Science Enterprise. Given the current limitations of computing power as well as limitations in our understanding of many relevant biological, chemical, and physical processes, it makes the most sense to use an incremental approach in linking together different Earth system components in coupled models. In this way, the effect of including the most critical interactions and feedback processes can be investigated through a series of numerical experiments, and the resulting coupled model simulations can be critically evaluated through comparison with observations.

Several successful examples exist of coupled models that represent some of the most critical interactions that link Earth system components. For example, the NASA Seasonal to Interannual Prediction Project (NSIPP) includes a realistic representation of physical and dynamical coupling between the atmosphere and ocean and of hydrological coupling between the atmosphere and the vegetated land surface. The resulting model is thus capable of simulating seasonal and interannual variability in the atmospheric circulation, temperature and moisture structure, and precipitation, as well as relationships with ocean surface temperature and land surface hydrology (soil moisture, snow accumulation, etc.). An important part of the NSIPP effort is maximizing the use of remotely sensed data by employing the most advanced data assimilation and initialization schemes for the moderately slow components of the coupled system: the upper ocean and the land surface. NSIPP is using a three-step approach to develop an experimental capability to predict significant climate variations on seasonal-to-interannual time scales. The first step consists in coupling component oceanic and atmospheric general circulation models (GCM's) and testing the coupled model for its ability to predict the interaction between the two media, especially as manifested in the tropical Pacific as El Niño and La Niña occurrences. The second step consists of coupling a land surface model with hydrology to an atmospheric GCM and testing the result for its ability to predict land surface hydrology and its evapotranpirative feedback to the atmosphere. Evapotranspiration feedback is especially important during the warm season over large continental areas. Predictions with both of these two-component coupled models are executed with prescribed forcing from the uncoupled component. The third step consists of coupling the atmospheric GCM to both the ocean model and the land surface model for three-way coupling. The resulting coupled system is then to be tested for its ability to predict both the simultaneous and lagged effects of El Niño and La Niña occurrences on the seasonal climate of North America and other regions of the world. The immediate goal is to make predictions with a useful level of skill up to a year in advance. Longer-term goals include extending predictive capability to interannual time scales and relating El Niño and other seasonal-to-interannual climate variations to decadal and longer climate system variability and trends.

NSIPP activities are connected both to the needs of other agencies, especially NOAA, and to other research efforts in the seasonal-to-interannual climate community. NSIPP coordinates with NOAA's Climate Prediction Center and will make its advances in seasonal-to-interannual prediction capability available to the Center for possible operational implementation. NSIPP has established a working science team of collaborating researchers from the broader community to help in achieving its goal. Some of the important tasks that the science team will assist with include assimilation of ocean data, improved representation of ocean/atmosphere coupling processes, inclusion of the effects of sea ice, testing of alternative component models in the coupled predictive system, and diagnostic evaluation of model simulations.

Similarly, the climate models developed at NASA's Goddard Institute for Space Studies (GISS) include realistic representation of individual and combined effects of different forcing factors on the Earth's climate, especially the role of aerosols on atmospheric climate, and the effects of variations in solar radiation, land surface properties, and atmospheric ozone distribution. Calculating the response of the model atmosphere to these combined forcing factors and comparing the simulated response to global observation records are essential aspects of this work. The focus of the GISS modeling effort is directed mainly (though not exclusively) toward the causes of climate variability and change on decadal and longer time scales.

GISS is engaged in making major improvements to its component models in order to represent the total climate system with greater fidelity. A series of workshops is being held in order to bring in community expertise and to develop collaborative modeling activities with outside researchers. So far, workshops on ocean, land surface, and sea-ice modeling and coupling with atmospheric models have been held, along with workshops on atmospheric aerosol modeling and on the observational data base needed for model evaluation. Workshops on other aspects of model development, testing, and application will be held as warranted. Among the applications of GISS models are the role of aerosols in radiative forcing of the climate (both directly and indirectly through cloud modification), the role of solar variability and deeper ocean overturning on climate variations, and feedbacks to climate by land surface vegetation and sea-ice extent. GISS participates in the five-year assessments of the Intergovernmental Program on Climate Change (IPCC) as well as in national climate assessment activities. Increased coordination of GISS modeling activities with those of NSIPP and with other major modeling activities is being developed.

Modeling research at the University of Wisconsin and other institutions that is focused on linking our understanding of the terrestrial biosphere with that of the physical climate system has yielded two important advances. First is the recent development of "Dynamic Global Vegetation Models" (DGVM), which can be used to simulate transient changes in ecosystem processes and vegetation cover in response to climate change or land use. Second is the coupling of terrestrial ecosystem models with atmospheric General Circulation Models. Fully interactive, coupled climate-vegetation models will be able to evaluate vegetation feedbacks on the Earth's climate system, including those resulting from changes in land cover and land use.

Likewise, there has been appreciable interest in linking together atmospheric chemistry and climate models in order to simulate feedbacks between atmospheric chemistry and climate changes, as well as assess the relative impacts of slow climate variations and chemical changes on ozone distribution. Although the ultimate aim is to fully integrate complete atmospheric chemistry and climate models, much of the work to date involves either simplified representation of chemistry in climate models or simplified representation of climate dynamics in atmospheric chemical models. However, the nature of the dynamical, radiative, and chemical feedbacks associated with ozone and water vapor changes in the upper troposphere and lower stratosphere require that fully interactive and balanced coupling be developed to address these problems.

Models that simulate the effect of aerosols on clouds constitute another area of linkage. It has long been recognized that the presence of aerosols can affect the distributions and properties of clouds, but models that represented this interaction did not exist. Now, modeling efforts have begun to represent the formation of aerosols from precursors, their microphysical evolution and interactions with clouds. At this time, such models typically must simplify the simulation of aerosol microphysical processes, but it is increasingly clear that the complexity of aerosol composition and interactions with clouds can only be simulated by models designed to provide reasonably complete treatment of aerosol and cloud microphysics. Progress in this area is rapid and will be facilitated by a significant increase in space-based observations of global aerosol distribution and properties. Finally, simulations of the role of aerosols in providing nutrients for oceanic organisms are just beginning. Such models need to couple ocean dynamics, ocean biogeochemistry, and atmospheric processes that are responsible for nutrient deposition into the surface layers of the ocean. Again, the availability of global aerosol data and observations of biological activity in the ocean is driving the development and evaluation of such models.

A major challenge to the ESE modeling program is, therefore, to facilitate linking models for different components of the Earth system. Achieving this linkage requires the availability of well studied component models as well as sufficient understanding of the processes that link the components, particularly boundary layer processes that control the exchanges of momentum, energy, water, and trace chemicals between these components. For instance, models attempting to link the exchange of trace gases between the ocean and atmosphere must include a realistic representation of air-sea exchange mechanisms and their effects on trace gas distributions in both the surface layer of the ocean and the boundary layer of the atmosphere. The detailed knowledge necessary to develop rigorous (or sufficiently well parameterized) coupled models typically comes from the process models described in section 7.2.1.

The incremental strategy used by the Earth Science Enterprise in linking component models should help assure a smooth progression in state-of-the-art models despite the limitations in computing power and associated software systems that now exist. The strategy allows for different component model versions to be used in differing linkage studies. The specific structure of a coupled model is determined by the application for which it is intended. For example, fairly high-resolution atmospheric general circulation models will be needed to simulate processes that couple the atmosphere to land surface hydrology, for prediction of the evolution of the chemical composition of the atmosphere in a changing climate, or for diagnostic studies of atmospheric transport of carbon dioxide from various terrestrial and oceanic sources.

7.3.4 Earth System Models

In the longer term, the ultimate objective is the construction of fully interactive coupled models that include the full range of physical, chemical, and biological processes occurring in the Earth system. Such comprehensive models are conceivably needed to identify and assess the non-linear impacts of the combined interactions and feedback processes that operate in the Earth system. In particular, coupling the three classes of processes (physical, chemical, and biological) noted above would represent a significant advance over most existing coupled models, which tend to include at most two among these three classes, as described in the previous section. Future fully coupled models should also be capable of simulating multiple spatial and temporal scales, given the great interest in both the scientific and policy communities for information across a wide range of scales. Such coupled models would be especially useful for regional and global assessments of future environmental trends and would help document the full diversity of expected changes in the total Earth system. Variable grid and nested models may play an important role in allowing for high spatial resolution where needed without sacrificing computational efficiency.

The development of this class of models will require a careful analysis of the quality of the component models, the knowledge of interactions and feedback processes being considered, and the availability of adequate computational resources. Clearly, it makes little sense to couple two or more inadequate component models into an even more unreliable linked model to represent complex interactive phenomena when the underlying processes are not well known. On the other hand, much can be learned even from imperfect models. One cannot wait for perfection in each component model to begin learning about emergent phenomena resulting from first-order interactions between various components of the Earth system. For this reason, a detailed ESE research strategy for the development of fully interactive Earth system models has not yet been formulated, although it seems clear that the greatest challenges in this area will be integrating biological models into the physical modeling framework. This task will become particularly difficult for longer-term simulations, as our knowledge of the biosphere responses to changes in climate, atmospheric trace gas composition, etc. over long periods of time is much more limited than our knowledge of shorter-term responses. The Earth Science Enterprise expects to make significant investments to include chemical and biological processes in coupled earth system models over the coming few years.

7.3.5 Assessment Models

The atmospheric chemistry community has a long history of supporting assessments of the impacts of various disturbances on the atmospheric environment. The most widely known among those are the periodic Scientific Assessments of Ozone Depletion, carried out on behalf of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) as well as the assessment of climate forcing factors on behalf of the Intergovernmental Panel on Climate Change (IPCC, 1995). Comparable studies have been organized in cooperation with NASA's Office of Aero-Space Technology to assess the impact of projected aircraft traffic on the composition of the atmosphere and climate. Model simulations, incorporating given scenarios for changes in relevant forcing factors, constitute the most compelling means to estimate the potential impacts of anticipated changes on all aspects of the global environment. For these assessments, both retrospective diagnostic model studies simulating the past evolution of the global environment using known or assumed changes in forcing, and prognostic studies aiming to simulate the potential future evolution in response to anticipated changes in forcing, are effective means to provide the scientific information required by responsible authorities. The international assessments of global climate change sponsored by the IPCC and participating nations make extensive use of nested (fine-mesh) climate assessment models to explore the full range of potential environmental impacts on the appropriate regional scales. The application of such models as they become available will form an important part of NASA’s contributions to the national assessment of climate change carried out in the US as well as to IPCC assessments. Similarly, ecological models will be applied to explore scenarios of ecosystem change within national environmental assessments as is being done now using the VEMAP models for the U.S. in the National Assessment of Potential Consequences of Climate Variability and Change.

7.4 LINKAGE OF OBSERVATIONS AND MODELS

Although observations and models have been discussed separately in the preceding sections, it is important to emphasize that the maximum benefit of each can only be achieved by combining both resources. NASA’s strategy is designed to assure very close linkage between the observational and modeling efforts. Some reasons for this linkage are obvious: initial conditions of models used for prediction should be as accurate as possible, and global observations provide an accurate means to initialize many model parameters. Similarly, the evaluation of global model performance depends on the availability of sufficient observed data, and the global observations made by NASA are among the primary data sets that can be used for this purpose.

Other connections between models and observations are perhaps less obvious. Two of these are inverse modeling and data assimilation. In the former, a global model is used to help assess some elements of the earth system (for example, the sources and sinks of long-lived trace gases) given observations of the distribution of a parameter of interest and knowledge of the other environmental processes that affect it. Data assimilation assures the optimal combination of observations and short-term predictions of a global model to provide accurate, physically consistent, and globally distributed data sets. Details of NASA's activities in these areas are given in the following sections.

7.4.1 Inverse Models

Most Earth system modeling is done in the direct mode by calculating the likely environmental response to a known or assumed evolution of forcing factors. However, in many cases, the forcing factors and especially their geographic distribution are not completely known. In such cases, models may be used together with observations of the response of the Earth system to infer the values of the forcing factors. This approach is known as inverse modeling, as the intent is to "go backwards" and infer what forcing factors gave rise to the observed response.

The application of inverse modeling is critically dependent upon the availability of accurate and complete observational data to characterize the response of the environmental parameters of interest and their spatial and temporal changes. The global data sets provided by the Earth Science Enterprise, as well as the data provided by its partner agencies, are critical elements of any strategy using inverse modeling. For instance, the sources and sinks of chlorofluorocarbons (CFC's) have been estimated, using atmospheric tracer transport models, on the basis of surface concentration data obtained by the AGAGE ground-based observation network described in Chapter 3. Annual emission inventories of CFC's have been estimated and compared with known production figures and their corresponding geographical distributions using similar inverse modeling techniques. More recently, there has been significant interest in using inverse modeling to better constrain our knowledge of emission and uptake of carbon dioxide. Ground-based measurements of CO_2 concentration made by the flask sampling network of NOAA's Climate Monitoring and Diagnostics Laboratory provide the crucial information for this purpose. A continued emphasis on inverse modeling studies of CO_2 is expected as new information on the terrestrial and marine biosphere become available from the Terra satellite. In the near future, inverse modeling is expected to be used for a variety of other trace gases, including carbon monoxide and methane observed by the MOPITT sensor aboard Terra.

In order for the inverse modeling approach to give useful results, it is necessary that either only one relevant forcing factor is inadequately known or that one forcing factor is dominant over all others. Otherwise, it is difficult to determine the spatial and temporal arrangement of forcings that results in the observed environmental variables. For example, inverse modeling has been used at NASA/GISS and elsewhere in an attempt to determine the role of solar variability (imperfectly known earlier than the last few decades) in past climate variations. In order for the results to be meaningful, one has to either know the other forcing factors such as greenhouse gases quite accurately or assume that, at least in some eras, solar variability was the dominant forcing.

7.4.2 Data Assimilation and Model Evaluation

Data assimilation is the process by which observations and model simulations are optimally combined to provide environmental variable fields that are accurate, internally consistent, and geographically homogeneous. The "direct models" that are used in this process are not perfect and may have a number of systematic errors or limitations. Indeed, the added value of data assimilation methods strongly depends upon the predictive skill of the model which is used to bring forward in time the "memory" of past observations. Furthermore, the internal consistency of data assimilation products reflects, to a considerable degree, the specific process-level assumptions made in the model, resulting in a "model climate" that may differ significantly from the real climate. Since the forward model prediction used in most assimilation systems is short (typically 6 hours in atmospheric assimilation systems), most relevant parameters are usually quite accurately carried forward, though there are exceptions (e.g. winds in the atmospheric jet streams). However, if predicted variables are not updated by observations in nearly every cycle, and in some regions and times they may not be, the predicted fields will indeed show drift toward those of the model climate. Thus, considerable care must be given to the quantitative interpretation of findings based on data assimilation products.

Nevertheless, the need for internally consistent and globally homogeneous data sets is so pressing that Earth system scientists will continue to make use of data assimilation products, even if the models do not provide perfectly accurate descriptions of the relevant parameters when run in a predictive mode. For this reason, NASA will continue to devote significant effort to improving scientific capabilities in this domain and reducing the residual errors in analysis products. The role of data assimilation is discussed in Chapter 4 in the context of meteorological and climatological applications and Chapter 5 in the context of oceanic applications. Applications of data assimilation to chemical and biological problems are still in their relative infancy, although there is increasing interest in such applications.

The scientific value of much of the new observational data produced by the ESE would be enhanced by being merged into consistent global data sets incorporating multiple related variables such as provided by “multivariate” data assimilation systems. Existing data assimilation systems, principally applicable to meteorological and oceanographic data, will need to be expanded to allow for the incorporation of different classes of measurements when new observing systems come on line. The ESE will vigorously encourage efforts to assimilate these new environmental observations, especially measurements not previously available on a global basis. Much of the effort in this area to date has focused on preparations for the assimilation of new data coming from the EOS Terra and Aqua missions. NASA's advances in assimilation systems and products will be shared with its operational partners, especially when improvement in the resulting products has been demonstrated with the assimilation of new types of observations.

As the range of assimilated variables expands, it is important that progress continues toward more capable and accurate assimilation systems. Continued research in data assimilation algorithms, especially as they relate to new types of measurements, will be an important element of NASA’s research program. Similarly, the accuracy of the global models that are used in the assimilation process must be assured. It is desirable that the direct models used in the assimilation process have close heritage to those used in Earth system simulation activities. Thus, the assimilation and modeling activities must be closely linked. In fact, data assimilation provides an objective tool for evaluating the adequacy of global models and can highlight inconsistencies between observed and analyzed fields. In this way, specific model deficiencies can be identified, suggesting further model improvements.

A significant focus of NASA’s current research in data assimilation is improvement of the core assimilating model used by the GSFC Data Assimilation Office (DAO). The short-term objective is to implement a higher resolution version (with a one degree by one degree grid) of the current assimilation system in order to realistically resolve meteorological fronts and other dynamically significant small-scale features of the atmospheric circulation. The DAO is also experimenting with use of a variable-grid version of the assimilating model that will have the capability of producing very high resolution in limited regions while retaining continuity with global atmospheric circulation and avoiding the numerical problems of nested grids. A major collaborative activity has been initiated with the National Center for

Atmospheric Research (NCAR) in the development of a new assimilating model. This model uses a modern semi-Lagrangian advection algorithm to conserve flux quantities and to provide an order-of-magnitude increase in computer power over its predecessor. This model will also facilitate possible replacement of current physical parameterization schemes by others being developed by the climate modeling community. This collaboration is one example of the interagency coordination that is desired in the broad climate modeling and assimilation area.

Longer-term objectives of the DAO include implementing more advanced assimilation methods based on Kalman filter concepts and continuous updating of variable fields. Also, the DAO plans to generate reanalyzed model-assimilated data sets for up to 50 years using a consistent assimilation scheme for the entire time period. Such reanalyzed data sets are of great value for detection of climate variations and trends as well as providing a consistent data base for a wide range of climate diagnostic studies. The DAO is currently assimilating atmospheric observations along with some land surface ones but will eventually integrate assimilation of ocean, cryospheric, and other land surface data into a more comprehensive assimilation activity. A major challenge for the DAO is developing the capability to do timely assimilation of new kinds of space-based data as they become available.

As was noted in the previous section on models, data assimilation provides a significant burden for the computational systems used. In particular, data assimilation involves significant input and output throughout the assimilation process, and advances in computer hardware and software designed to facilitate data assimilation must pay particular attention to ensuring the availability of both rapid computation speed and movement of data into and out of the assimilation system. Also, it is worth noting that the high spatial resolution desired in the assimilation systems of today and tomorrow will require significant storage capacity as well as the rapid input and output noted earlier. The developers of data assimilation systems will need to pay close attention to evolving computational capability and assure that the appropriate software systems and interfaces are developed to maximize the ability to capitalize on developments in computer hardware.

7.4.3 Model Evaluation and Inter-comparison

In the previous section it was noted that data assimilation provides one of the best ways to evaluate computational models because of the objective way in which model simulations are regularly confronted with observational data, thereby providing a means to quantitatively determine areas of inconsistency between models and observations. By continually comparing model products with measurements, data assimilation quantifies the mismatch between observations and model predictions and provides clues for further model improvements. The interactive optimization of model and data analysis is a systematic, structured, and open-ended learning process and is perhaps the single most important benefit of data assimilation in a research mode. This linkage has been successfully exploited in numerical weather prediction, and the challenge for the broader Earth science community is how to extend the application of assimilation systems to all relevant components of the Earth system. NASA places high emphasis on the evaluation of model performance through direct comparison with the rich sets of observational data collected by its observing projects. At the integrated model level, NASA sees the assimilation of global observational data as the principal means for verification of model results and validation of the representations of component processes. From this perspective, data assimilation is an excellent way to determine the quality of models used for diagnostic and predictive simulations as well as for assimilation.

Observations can also be used in a more traditional way for evaluating models. Several focused inter-comparisons of models with relevant observations have been or will be carried out, either collectively by an informal group of investigators or under the auspices of peer-led international scientific groups, such as the International Global Atmospheric Chemistry project's Global Integration and Modeling activity and the WCRP's Atmospheric and Coupled Model Inter-comparison Projects (AMIP and CMIP).

Focused inter-comparisons of models with measurements have also been carried out for atmospheric chemistry models under the auspices of NASA's Office of AeroSpace Technology. These inter-comparisons also compare similar models to one another; this is important for understanding model-to-model variability, especially when there are insufficient data for quantitatively evaluating the processes of particular interest in the models. NASA places a strong emphasis on further quantitative evaluation and intercomparison of these models.

7.5 SUMMARY OF FUTURE RESEARCH DIRECTIONS

This section summarizes the principal directions for NASA observational and research activities envisaged in the next ten years. These prospects are based on a vision of new opportunities for research and technological breakthroughs, continued funding of Earth system science, the availability of the needed operational observing systems and computational resources, all of which are obviously not known in any detail.

7.5.1 Observational Research Directions

The first, and most obvious, direction of future observational activities in support of Earth system science is the proliferation of the observing systems capable of providing the same type of measurements as obtained today, such as multi-spectral imagery of the Earth's surface and clouds, radar imaging of terrain, and a range of atmospheric sensors on both operational and research environmental satellite systems. There are several causes for this proliferation: the increase in the number of space-faring countries that desire to engage in scientific research and/or operational data collection from space, new technologies that allow for miniaturization, integration of spacecraft and optical sensors, and overall cost reduction, and finally the increasing activity of the commercial sector in obtaining its own data. A major challenge to come from this proliferation will be ensuring the consistency of data sets for environmental parameters of scientific and/or operational interest.

The multiplicity of observing systems can leave the user with a complex set of choices: Which data set(s) do I use? On what basis do I choose? Can I put together an integrated data set that covers multiple instrument data sets, especially if they have been calibrated and validated through different procedures and protocols? If I need to "piece together" a long-term data set from several shorter-term data sets, how could I minimize discontinuities, especially if the assembled data set involves instruments from multiple providers? How can I be assured that data sets obtained primarily for operational purposes will be useable for longer-term global change studies? What do I do if I feel a need to create a new historical data set based on reprocessing of those previously obtained, especially if those were from multiple providers? Successfully answering these questions will involve the development of new relationships between research, operational, and commercial organizations, and require enhancements in the degree to which different agencies cooperate with each other.

Another direction for future advances in Earth system science is the exploitation of technological breakthroughs that may enable totally new kinds of observations. In the world of space-based measurements, there are five major areas of advancement that can be expected in the not-too-distant future and would have important implications for earth science research: (1) dramatic advances in the utilization of active optical sensors (lidars) capable of probing the lower reaches of the atmosphere, the land surface (and potentially, the topmost layer of the ocean) with great vertical resolution; (2) progress in active and passive remote sensing techniques operating at relatively low microwave frequencies that can penetrate relatively dense media (e.g., vegetation, snow, upper soil layers); (3) refinement of extremely precise geodetic and gravity field measurements that will give access to hitherto hidden properties such as changes in the distribution of water masses near the surface of the Earth; (4) development and implementation of new distributed observing systems involving multiple spacecraft, especially those that provide good geographical coverage of atmospheric parameters with high vertical resolution (mainly GPS based); and (5) expansion of quantitative measurement to include significantly improved time resolution, as may come from a next generation of geostationary sounding instruments, observations made from the L-1 Lagrange point, or modest constellations of spacecraft in staged low earth orbits.

7.5.2 Modeling Research Directions

The "holy grail" of Earth system modeling is to develop a unified comprehensive model that includes all possible linkages and interactions among the component parts of the system. With this model, interactions could be turned off to test the sensitivity of the Earth's variable environment to various processes or forcings, or replaced with simplified representations (e.g., climatological or similarly specified values) to reduce the computational load. While there is no doubting the inspirational value of this ultimate goal, most interesting and useful scientific applications can and likely will rely on more specialized modeling projects, each focused on a specific subset of relevant interactions and feedbacks. Even though there may not be much practical value in attempting to develop a "model of everything", care needs to be taken that more specialized models do not overlook or trivialize interactions and feedbacks that may in fact be significant for the given application.

The fact is that the on-going, possibly indefinite, progress in computational capabilities will drive the development of Earth system models. Advances in computer technology during the next decade will allow, for the first time, compiling and running models that actually embrace a wide enough range of spatial and temporal scales (Reynolds numbers) to explicitly simulate the dynamical connections between different natural categories of phenomena, for instance in the case of the atmospheric circulation:

- Linking global-scale changes in the atmospheric general circulation to organized weather systems such as tropical cyclones, frontal systems or squall lines.
- Linking organized weather systems to convective-scale phenomena, tornado- and rain-generating storms, and a diversity of terrain and terrestrial ecosystems (e. g. cloud ensemble models; limited-area atmospheric-hydrologic models, etc.).
- Linking cloud-scale dynamics to microphysical and chemical processes.

Another very significant direction of progress is the introduction of progressively more realistic representations of linkages between different types of processes, e. g. climate- transport dynamics-chemistry interactions, climate-biosphere-hydrology interactions, ice-sheet and sea-ice dynamics and forcing by atmospheric and oceanic circulations, climatic impacts on the spreading of disease vectors, etc. In other words, the emphasis of model development efforts will shift from representing large-scale dynamical transport and plane-parallel approximations of radiative and other fluxes, toward the detailed physical, chemical and biological processes that are actually taking place in the system. More attention will need to be given to the integration of modeling efforts and observational field studies, each supporting the other for optimal scientific advances. Recourse to ever more sophisticated explicit or lightly parameterized representations of basic processes will be essential in achieving effective synergy between model and experimental research.

Finally, a hallmark of the ESE modeling strategy is continued or increased emphasis on testing or validating model results against observations of the real Earth system. While observations without the appropriate model-generated theoretical framework may be more confusing than helpful, data-free modeling is not likely to be particularly productive either. NASA will support preferentially modeling developments that clearly can take advantage of the wealth of observational information collected by its global observing systems. In this regard, NASA expects that other Earth system model developments in the future will develop and utilize model-based observational data assimilation systems that are similar in purpose to those used successfully today for numerical weather prediction.

7.6 REFERENCES

NRC, 1998: *The Atmospheric Sciences Entering the Twenty-First Century*; National Research Council; Board on Atmospheric Sciences and Climate; National Academy Press, Washington, DC.